The ionized absorber and nuclear environment of IRAS 13349+2438: multi-wavelength insights from coordinated Chandra HETGS, HST STIS, HET and Spitzer IRS

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ABSTRACT

We present results from a multi-wavelength infrared (IR)-to-X-ray campaign of the infrared bright (but highly optical-ultraviolet extincted) quasi-stellar object (QSO) IRAS 13349+2438 obtained with the Chandra High Energy Transmission Grating Spectrometer (HETGS), the Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS), the Hobby–Eberly Telescope (HET) 8 m and the Spitzer Infrared Spectrometer (IRS). Based on HET optical spectra of [O III], we refine the redshift of IRAS 13349 to be z = 0.108 53. The weakness of the [O III] in combination with strong Fe II in the HET spectra reveals extreme Eigenvector-1 characteristics in IRAS 13349, but the 2468 km s\(^{-1}\) width of the H\(\beta\) line argues against a narrow-line Seyfert 1 classification; on average, IR, optical and optical-ultraviolet (UV) spectra show IRAS 13349 to be a typical QSO. Independent estimates based on the H\(\beta\) line width and fits to the IRAS 13349 spectral energy distribution (SED) both give a black hole mass of \(M_{\text{BH}} = 10^9 \, M_\odot\). The heavily reddened STIS UV spectra reveal for the first time blueshifted absorption from Ly \(\alpha\), N V and C IV, with components at systemic velocities of \(-950 \, \text{km s}^{-1}\) and \(-75 \, \text{km s}^{-1}\). The higher velocity UV lines are coincident with the lower ionization (\(\xi \sim 1.6\)) WA-1 warm absorber lines seen in the X-rays with the HETGS. In addition, a \(\xi \sim 3.4\) WA-2 is also required by the data, while a \(\xi \sim 3\) WA-3 is predicted by theory and seen at less significance; all detected X-ray absorption lines are blueshifted by \(\sim 700\)–\(900 \, \text{km s}^{-1}\).

Theoretical models comparing different ionizing SEDs reveal that including the UV (i.e. the accretion disc) as part of the ionizing continuum has strong implications for the conclusions one would draw about the thermodynamic stability of the warm absorber. Specific to IRAS 13349, we find that an X-ray–UV ionizing SED favours a continuous distribution of ionization states in a smooth flow (this paper) versus discrete clouds in pressure equilibrium (previous work by other authors). Direct detections of dust are seen in both the IR and X-rays. We see weak polycyclic aromatic hydrocarbon (PAH) emission at 7.7 \(\mu\)m and 11.3 \(\mu\)m which may also be blended with forsterite, and 10 \(\mu\)m and 18 \(\mu\)m silicate emission, as well as an Fe L edge at 700 eV indicative of iron-based dust with a dust-to-gas ratio >90 per cent. We develop a...
geometrical model in which we view the nuclear regions of the QSO along a line of sight that passes through the upper atmosphere of an obscuring torus. This sight line is largely transparent in X-rays since the gas is ionized, but it is completely obscured by dust that blocks a direct view of the UV/optical emission region. In the context of our model, 20 per cent of the intrinsic UV/optical continuum is scattered into our sight line by the far wall of an obscuring torus. An additional 2.4 per cent of the direct light, which likely dominates the UV emission, is Thomson-scattered into our line of sight by another off-plane component of highly ionized gas.

**Key words:** galaxies: active – quasars: absorption lines – quasars: emission lines – quasars: individual: IRAS 13349+2438 – ultraviolet – galaxies: X-rays: galaxies.

1 INTRODUCTION

IRAS 13349+2438, hereafter ‘IRAS 13349’, (z = 0.10764 – Kim et al. 1995; updated here to z = 0.108 530 based on the three times higher resolution Hobby–Eberly Telescope (HET) spectra reported in this paper) is a prototype infrared-luminous quasar with a bolometric luminosity of \( \geq 2 \times 10^{46} \) erg s\(^{-1}\) (Beichman et al. 1986). Images of the host galaxy and nearby environment show the galaxy to be spiral-like, with a possible companion at \( \sim 5 \) arcsec along the minor axis (e.g. Hutchings & McClure 1990). Evidence for tidal structure suggests that the object may have interacted with the companion, and this could supply gas and dust to the nucleus, fuelling quasar activity and enhancing nuclear obscuration and scattering. Indeed, IRAS 13349 has a broad emission-line optical spectrum that becomes heavily reddened at shorter wavelengths and exhibits high optical continuum and emission-line polarization (Wills et al. 1992, hereafter W92). The observed polarization rises strongly towards shorter wavelengths, but the optical polarized flux spectrum is indistinguishable from a typical, unreddened quasar (Hines et al. 2001). These polarization properties indicate that observers see the quasar’s nucleus via both a direct, but attenuated, light path and a scattered light path (W92; Hines et al. 2001). In addition to its high luminosity and spectral variability, IRAS 13349 also exhibits strong Eigenvector-1 characteristics (strong optical Fe\(\text{II}\) emission and weak [O\(\text{II}\)] relative to H\(\beta\); Boroson & Green 1992). It is typically identified to be radio-quiet, although weak 4.87 mJy radio emission has been reported at 6 GHz by Laurent-Muehleisen et al. (1997).

The observed high-X-ray flux and large-amplitude X-ray variability indicate that a large fraction of the X-ray emission is seen via a direct, rather than a scattered, path. As such, IRAS 13349 has been the subject of a number of X-ray studies that have helped to clarify the physical processes in the inner regions of the quasar nucleus. Using XMM–Newton EPIC data, Longinotti et al. (2003) made a detailed analysis of the IRAS 13349 ionized reflection spectrum and relativistic Fe emission line. At lower energies, X-ray studies based on the ROSAT Position Sensitive Proportional Counter (PSPC; Brandt et al. 1996) and ASCA (Brandt et al. 1997), combined with optical/near-infrared extinction estimates argue for obscuration by dusty, ionized gas. Studies with modern day high spectral resolution instruments on board XMM–Newton (Sako et al. 2001) and Chandra (Holczer, Behar & Kaspi 2007; Behar 2009; also this paper) reveal additional complexity in the absorbers [most notable an unresolved transition array (UTA) of 2p–3d inner-shell absorption by iron M-shell ions, dubbed the UTA by its discoverers, Sako et al.] and allow direct measurements of the dust composition (this paper) in the host galaxy.

In this paper, we present a comprehensive analysis of the absorber properties of this quasar, based on our high spectral resolution, multi-wavelength campaign, involving X-ray (with the Chandra High Energy Transmission Grating Spectrometer, HETGS), ultraviolet [with Hubble Space Telescope (HST) Space Telescope Imaging Spectrograph (STIS)], optical (HET: 8 m) and infrared (Spitzer Infrared Spectrometer, IRS) observations. The Chandra and HST observations are simultaneous, HET near simultaneous, and Spitzer IRS taken 1.25 yr later as part of the GTO programme of George Rieke (GR). These high-quality data allow us to address, in detail for a specific luminous system, several issues of broader importance in active-galaxy absorption studies. These include the apparent presence of dust in some ionized absorbers and its implications for interpreting observations; the relation of ionized absorbers to other nuclear components, including accretion discs, tori and scattering material; the relation of the spectral energy distribution (SED) to the structure of ionized absorbers and the potential for feedback into host galaxies by outflowing nuclear winds.

The paper is organized as follows. In Section 2, the multi-wavelength data are presented, to be followed by a plasma diagnostic approach to the line analysis in Section 3. In Section 4, we combine our multi-wavelength data with additional Infrared Space Observatory (ISO) and IRAS archived observations to produce an observed SED that is used to determine a theoretically motivated ionizing spectrum affecting the warm absorber properties; this then is used to generate ion populations with XSTAR for our spectral fitting. This will set the stage for Section 5 considerations on the warm absorber behaviour as established by thermodynamic stability arguments (Section 5.1) and complex line-of-sight geometry through dust (Section 5.2). We adopt \( H_0 = 73 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_M = 0.25 \) and \( \Omega_{\Lambda} = 0.75 \) throughout this paper.

2 OBSERVATIONS AND DATA REDUCTION

As part of a multi-wavelength campaign to better understand the global physical processes, absorber kinematics and geometry of IRAS 13349, we observed this nearby quasar using spectrographs on Chandra (X-ray), the HST (ultraviolet), the HET 8 m (optical) and the Spitzer Space Telescope (infrared; Werner et al. 2004). Observations performed with Chandra, HST and HET were nearly simultaneous and of comparable spectral resolution (\( R \sim 1000 \)), while ‘high’ (\( R \sim 600 \)) and low-resolution (\( R \sim 70–120 \)) IR spectra from Spitzer were obtained \( \sim 1.25 \) yr later as part of the GTO programme of GR.

2.1 X-ray observations with the Chandra HETGS

IRAS 13349 was observed with the Chandra HETGS (Weisskopf et al. 2002; Canizares et al. 2005) over several days in 2004 February for a total of \( \sim 295 \) ks of usable data as summarized in Table 1. Plus and minus first-order (±1) spectra were extracted using the
2.3 Near simultaneous optical observations with the Hobby–Eberly 8 m

Since IRAS 13349 shows large-amplitude variability at X-ray wavelengths, we also obtained a near-simultaneous spectrum of it with the 8-m HET (Ramsey et al. 1998) to constrain its optical properties during the Chandra and HST observations. (We note that while the HET\(^2\) is officially designated a 9.2-m telescope, we conservatively refer to it here as an 8-m class given that this is the average equivalent aperture for a typical observation – see Schneider et al. 2000.) HET observations were obtained on 2004 February 26 with the Marcario low-resolution spectrograph (Hill et al. 1998a,b). The observations were taken with a 600 line mm\(^{-1}\) grating, a slit width of 0.1 arcsec and a GG385 blocking filter, resulting in a resolving power of 1300 over the observed wavelength range 4300–7300 Å. The total exposure time of 1283.5 s was split among four sub-exposures.

For flux calibration, we observed the white-dwarf standard Feige 34 during the middle of the night, two hours prior to our observation of IRAS 13349. Exposures on a Cd-Ne arc lamp were used to determine the wavelength scale, with zero-points adjusted using the night-sky lines in our spectra. Final flux-calibrated spectra were extracted with the standard IRAF reduction codes for single-slit data.

2.4 Infrared observations with the Spitzer IRS

Low-resolution (\(R = 70–120\)) and high-resolution (\(R \sim 600\)) infrared spectra were obtained as part of the GTO programme of GR (PID: 61) on 2005 June 7 with the Infrared Spectrograph (IRS, Houck et al. 2004) on the Spitzer Space Telescope (Werner et al. 2004) using the standard staring mode. In each spectroscopic module, the source was observed at two nodding positions, and exposure times were set to 2 \(\times\) 5 \(\times\) 14 s in SL (Short–Low) and LL (Long–Low), as well as 2 \(\times\) 5 \(\times\) 120 s and 2 \(\times\) 10 \(\times\) 60 s in SH (Short–High) and LH (Low–High), respectively.

The low-resolution spectral data (LRS) were reduced, from the basic calibration data (BCD) files, following the standard procedure given in the IRS Data Handbook.\(^3\) The basic steps were bad-pixel correction with IRSCLEAN V2.1, background subtraction using the off-source slit, as well as optimal extraction and wavelength/flux calibration with the Spectroscopic Modelling Analysis and Reduction Tool suite (SMART V8.2.1; Higdon et al. 2004), for each nodding position. Spectra were then nod-averaged to improve the S/N ratio.

The flux calibration appeared consistent between the different modules, with differences less than 5 per cent, and this allowed us to combine all the spectra to cover the 5.2–35 \(\mu\)m spectral range (4.7–32 \(\mu\)m rest frame). Nevertheless, the continuum at 25 \(\mu\)m showed a multiplicative offset from the IRAS 13349 photometric flux at 25 \(\mu\)m obtained from the\(^4\) IRAS Point Source Catalog (hereafter, IRAS-PSC; Beichman et al. 1988). Unfortunately, there is no associated multiband imaging photometer for Spitzer (MIPS) 24 \(\mu\)m photometry during the epoch of the Spitzer IRS observation, so we cannot rule out the possibility that the object has varied in this energy band. However, given that IRAS 13349 is radio quiet, and that the shape of the SED suggests that the mid-IR is produced by thermal emission from dust heated by the central engine, we assume that the mid-IR has not varied. We therefore scaled the entire

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\(^2\) http://www.as.utexas.edu/mcdonald/het/het_gen_01.html
\(^3\) http://ssc.spitzer.caltech.edu/irs/irsinstrumenthandbook/IRS_Instrument_Handbook.pdf
\(^4\) http://tdc-www.harvard.edu/catalogs/iras.html

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1 http://space.mit.edu/CXC/ISIS/ (Houck & Denicola 2000)
spectrum by a factor of 1.077 to match the (un-colour-corrected) IRAS-FSC flux density measurement of $0.84 \pm 0.06$ Jy at 25 $\mu$m. We reduce the high-resolution spectral data (HRS) in much the same way as previously described for the LRS, with the exception that full aperture instead of optimal extraction is employed, the distinction being that pixels along the dispersion axis have equal (full aperture) versus varied (optimal) weighting. Moreover, we could not remove background by on-source/off-source subtraction, due to the lack of off-source HRS background files in the IRS archives associated with the epoch of this observation. Therefore, we extract SL1, LL2 and LL1 backgrounds from the low-resolution data and fit with first-order polynomials. We then use these fits to remove the background contribution from the high-resolution spectra, giving a good match between the SH and LH continuum flux density level. Finally, the overall high-resolution spectrum is scaled by 1.077 to match the continuum flux density level at 25 $\mu$m to the IRAS 13349 IRAS-PSC photometric flux density at the same wavelength.

3 DATA ANALYSIS AND LINE DETECTIONS

The intent of this paper is to provide the highest spectral resolution multi-wavelength characterization of the IRAS 13349 spectrum to date, as a step towards a more detailed understanding of the structure of this quasar and its host galaxy. For this paper, we employ both a plasma-diagnostic approach to the analysis (this section), as well as photoionization modelling with XSTAR (Kallman & Bautista 2001) for a global analysis (Section 4) of the spectra based on the observed multi-wavelength SED.

3.1 The X-ray Chandra-HETGS spectrum

We begin initially with a plasma diagnostic approach to the line fits. To search for individual absorption and emission lines, HETGS spectra were binned by two, corresponding to half the spectral resolution, respectively 0.006$\AA$ and 0.012$\AA$ full width at half-maximum (FWHM), for the HEG and MEG. For these fits, we use a fifth-order polynomial to fit local continua, rather than a phenomenological broad-band continuum. Such an approach allows us to remove the broader fluctuations, thereby maximizing our ability to measure the narrow lines without assumptions about details of the continuum, which can be complex. Using this analysis procedure, we find the X-ray spectrum to be dominated by an ionized absorber giving rise to prominent H- and He-like absorption lines of oxygen, neon, magnesium and silicon, as well as absorption lines from a variety of iron ions, at a bulk outflow velocity in the range $-900$ km s$^{-1} \lesssim v_{\text{sys}} \lesssim -500$ km s$^{-1}$.

Since a comprehensive photoionization treatment of the IRAS 13349 absorber as tied to its SED and theory considerations, is explored in detail in Section 4, we concentrate here primarily on the key H- and He-like ions as a model-independent way of accessing the quasi-stellar object (QSO) hot plasma conditions for comparison with later analysis. For many of these key ions, high-order transitions, corresponding to a high-column-density warm absorber is detected (see Table 3). For these key ions, we derive the individual ionic column densities ($N_j$) based on a fit to the entire detected resonance series of lines from $n = 2$ to $xx$, where $xx$ is the highest transition detected; e.g. H-like 1$s$–$np$ Mg XII and He-like 1$s^2$–1$sp$ Mg XI are detected to $n = 4$ so that our fits to those series are to the Ly/He($\alpha$, $\beta$, $\gamma$, $\delta$) lines with their oscillator strengths locked to their tabulated value as found e.g. in Verner et al. (1996). The individual lines in the series are fit using Voigt profiles, although the derived $N_j$ is based on a simultaneous fit to all the detected lines in the series. In this way, we ensure the best possible determination of $N_j$ (Table 3) by reducing the possibility for false estimates resulting from saturated or contaminated lines. (Both saturated and contaminated lines can falsely indicate a line width and strength which is broader and has higher flux than what it truly is for the ion, thereby resulting in lower estimates for any given ionic column.) We note however, that despite these precautions, the spectral resolution of the Chandra HETGS, while the best available to date, is still not sufficient for probing at the level of measuring the 10–20 km s$^{-1}$ thermal widths of these ions. As such, $N_j$ estimates may only be lower limits. For thoroughness, we adopt a value for

| Ion  | $N_j$ detected | $v_{\text{blue}}$ (km s$^{-1}$) | $v_{\text{red}}$ (km s$^{-1}$) | $log N_j$ (cm$^{-2}$) | $N_j$ (10$^{21}$ cm$^{-2}$) |
|------|---------------|-------------------------------|-------------------------------|----------------------|-----------------------------|
| O VII | 2–∞          | −748±103$^{+126}_{-74}$      | 137±39$^{+97}_{-74}$          | 18.1±0.5             | 100                         |
| O VIII | 2–∞        | −595±107                     | 289±89$^{+62}_{-82}$         | 17.8$^{+0.2}_{-0.3}$ | 100                         |
| Ne IX | 2–∞          | −788±131$^{+168}_{-133}$     | 519±117$^{+173}_{-133}$      | 17.3$^{+1.0}_{-0.2}$ | 100                         |
| Ne X | 2–6         | −833±154$^{+264}_{-133}$     | 284±164$^{+139}_{-133}$      | 17.3$^{+0.3}_{-0.4}$ | 100                         |
| Mg XI | 2–4         | −578±212$^{+145}_{-79}$      | 150±79$^{+140}_{-140}$       | 17.4$^{+1.3}_{-0.5}$ | 100                         |
| Mg XII | 2–4       | −675±157$^{+132}_{-123}$     | 133±87$^{+87}_{-87}$         | 17.4$^{+0.4}_{-0.7}$ | 100                         |
| Si XIII | 2–3      | −537±134$^{+156}_{-48}$     | 48±447$^{+156}_{-48}$        | 17.4$^{+0.4}_{-0.7}$ | 100                         |

See corresponding curve-of-growth plots in Fig. 1.

$a$ Transitions in series which contribute to the best-fitting $N_j$; $\infty$ correspond to series limit.

$b$ Outflowing velocity measured against the laboratory wavelengths tabulated by Verner et al. (1996).

$c$ Turbulent velocity width (km s$^{-1}$) as determined from the series fit. See Section 3.1 for a discussion on caveats.

$d$ Corresponding ionic column density (cm$^{-2}$).

$e$ Corresponding ionic column density (cm$^{-2}$).

$\delta$ Corresponding equivalent hydrogen column assuming the solar abundance values given by Wilms, Allen & McCray (2000). Note however that the numbers assume an ionization fraction for all ions to be 50 per cent; as such, quoted numbers are only rough guides, and not to be directly taken at face value.
the turbulent velocity width \( b = 100 \text{ km s}^{-1} \) to approximate the Chandra-HETGS spectral resolving capabilities, for deriving the ionic columns noted in Table 3; we also detail the associated ionic columns based on fits where \( b \) is allowed as a free parameter. For Ne \( \text{IX} \) (and to a lesser extent Ne \( \text{X} \)), Fe contaminates many of the stronger lines in the series, resulting in a larger measured \( b \), and hence smaller \( N_j \).

It is also clear that the measured value of \( N_j \) strongly depends on \( b \) as best illustrated by the curve-of-growth (COG) plots in Fig. 1. Here, we plot COG calculations (which include the damping parameter as presented e.g. in Spitzer 1978) for different values of the turbulent width, which range from \( b = 10 \rightarrow 20 \text{ km s}^{-1} \) (\( \approx \) the thermal width value of the ion), to \( b = 100 \text{ km s}^{-1} \) (maximal resolving power of the HETGS), to \( b = 1000 \text{ km s}^{-1} \) (the approximate value derived by Sako et al. 2001 in their analysis of the XMM RGS spectrum). For each ion, two sets of curves corresponding to the \( 1 \rightarrow 2 \) (Ly/He \( \alpha \)) and \( 1 \rightarrow 9 \) (representing the series limit) transitions are shown. Overplotted as individual points on the curves are the values for the different transitions which are detected in our data, and which contribute in the series fitting of the \( N_j \) values listed in Table 3, for fixed values of \( b = 100 \text{ km s}^{-1} \). It is clear that for any given ion, a detection of the higher transition series better aids in the determination of \( N_j \). This is well illustrated in a comparison of the H- and He-like oxygen series which are detected to the series limit versus the H- and He-like silicon series, where only the \( \alpha (1 \rightarrow 2) \) and \( \beta (1 \rightarrow 3) \) transitions contribute significantly to the fitting. H- and He-like Ne have been excluded from the figure due to significant contamination from Fe. For the other ions in the figures, contamination to the line series comes from other velocity components of the same ions – e.g. for He-like O \( \text{VII} \), components 1, 2, 3 of the warm absorbers discussed in Section 4.3 all contribute to the line series at different velocities.

To assess further the presence of multiple velocity components, we generate velocity spectra based on the five strongest resonance transitions for the most prominent X-ray ions, namely H- and He-like ions of nitrogen, oxygen, neon, magnesium, aluminium, silicon and sulphur. (note that not all these are necessarily detected.) For each individual absorption line, a velocity grid from \(-4000 \rightarrow 4000 \text{ km s}^{-1}\) is generated centred around the rest wavelength of the particular line, i.e. zero velocity corresponds to the rest wavelength of the line of choice. The HETGS spectra of counts versus wavelength (initially binned by four) is remapped (through interpolation) to convert to the velocity space. Standard error propagation rules are invoked and the remapping retains the Gaussian nature of the errors (i.e. \( \sqrt{\text{counts}} \)). The velocity spectra of the five strongest resonance lines are then combined (errors are added in quadrature) to represent the velocity spectrum of the concerned ion. Fig. 2 shows the velocity profiles derived in the aforementioned way. The velocity is binned at \( 200 \text{ km s}^{-1} \) except for the bottom-most panel (i.e. for sulphur) where the binning is at \( 400 \text{ km s}^{-1} \). At wavelengths corresponding to the sulphur lines, which have been considered, the velocity resolution for HEG is >400 km s\(^{-1}\). To achieve the best results, we have used MEG spectra for N, O, Ne and Mg while resorting to HEG for Al, Si and S having higher energy transitions. The figure clearly shows detection of absorption for O, Ne, Mg, Al and Si. The N ions show a hint of absorption, whereas no absorption is detected for S ions. We have also looked for absorption in carbon, argon and calcium with no significant detection. For most of the ions the velocity profiles do not have a symmetric Gaussian distribution indicating the presence of more than one-velocity component. We will return to a discussion of the X-ray lines in Section 4.3.

3.1.1 Ionized and neutral emission lines

By far the strongest detected narrow X-ray emission line is the Fe \( \text{I} \) \( K\alpha \) fluorescent line at \( \sim 6.4 \text{ keV} \) (rest) with flux \( F_{K\alpha} \sim 4 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1} \) (Fig. 3; also Fig. 13). Another strong line of approximately equal strength appears at rest energy \( \sim 7 \text{ keV} \) (Table 8). This energy is best matched to Fe \( \text{I} \) K\( \beta \) but this gives an unphysically small ratio of \( 1\text{K}\alpha : 1\text{K}\beta \sim 1 \), when the ratio should be \( \sim 10 \). However, given the claim by Longinotti et al. (2003) based on XMM data for a complex iron line that has a narrow component on top of a relativistically broadened line, the most likely explanation for the measured similarities in the K\( \alpha \) and K\( \beta \) line fluxes here is that what we have measured in the Chandra data is only a small portion of the broadened line. Since a discussion of relativistic effects is not the goal of this paper, we will leave it at a reporting of the line measurements at high spectral resolution. An alternative possibility, especially given the line strength is that the emission is in fact due to Fe \( \text{XXVI} \) K\( \alpha \) at 6.96 keV. We have also checked the \( \sim 6\rightarrow 8 \text{ keV} \) spectral region for emission from other ions (e.g. 6.7 keV Fe \( \text{XXV} \) K\( \alpha \), 7.5 keV Ni \( \text{I} \) K\( \alpha \) and 8.26 keV Ni \( \text{I} \) K\( \alpha \)), but find no significant detections.

3.2 The UV HST STIS-MAMA spectra

To measure the UV fluxes, widths and redshifts of the emission and absorption lines, we used the IRAF\(^5\) task SPECFIT (Kriss 1994). As discussed in Section 5.2, the full continuum is a complex mix of direct light from the active nucleus that is heavily reddened combined with light scattered from dust, and perhaps free electrons also, that also suffers some extinction. We were unable to arrive at a model that fully matched the observed shape of the full continuum, so, to characterize the emission and absorption lines, we used an empirical approach that simply fits a power law that was locally optimized around each emission-line blend. Nearly all emission lines required both a broad (\( \sim 2500 \text{ km s}^{-1} \)) and a very broad (\( \gtrsim 7500 \text{ km s}^{-1} \)) component to obtain an adequate fit. Table 4 gives the fluxes, velocities and FWHM for the fitted emission lines. Velocities are relative to the systemic redshift of \( z = 0.10853 \), based on the observed redshift of the [O \( \text{III} \)] \( \lambda 5007 \) emission line in our HET spectrum (see Section 3.3 for details). The tabulated line widths are corrected for instrumental resolution by subtracting the resolution in quadrature from the measured widths. Wavelengths \( \lambda < 1720 \text{ Å} \) have the resolution of the STIS G140L grating as given in the STIS Instrument Handbook, ranging from 0.93 Å at 1350 Å to 0.81 Å at 1700 Å. Longer wavelengths have the resolution of the G230L grating, which is 3.40 Å.

Fig. 4 shows the merged UV spectrum of IRAS 13349 from 1150 to 3180 Å with the most prominent emission lines labelled. At the scale of this figure, Galactic and intrinsic absorption lines are not easily visible, aside from Galactic Ly\( \alpha \) absorption at 1216 Å, which is blended with geocoronal Ly\( \alpha \) emission. Otherwise, our HST spectrum of IRAS 13349 shows two prominent blueshifted absorption-line systems in Ly\( \alpha \), N \( \text{V} \) and C \( \text{IV} \). To measure the equivalent width, position and FWHM of each line, we use simple Gaussian absorption lines in our model to fit the spectrum. Fig. 5 shows full-resolution plots of the Ly\( \alpha \), N \( \text{V} \), Si \( \text{IV} \) and C \( \text{IV} \) regions of the spectrum overlaid with the best-fitting model.

\(^5\) IRAF (http://iraf.noao.edu/) is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 1. Curve-of-growth calculations representing \( n = 2 \) and \( n = 9 \) transitions for H-like 1s–1s\(_{np} \) and He-like 1s\(^2\)–1s\(_{np} \) transitions for different values of the turbulent velocity width \( b \). The plotted data points represent \( N_j \) values measured based on a simultaneous fit to all the lines detected for a given H- or He-like resonance series, assuming \( b = 100 \text{ km s}^{-1} \). For example, the plotted points represent a fit (with oscillator strengths locked in the appropriate ratios) to the detected \( n = 2 \) to \( n = 9 \) lines of He-like 1s\(^2\)–1s\(_{np} \) O vii, whereas a fit to the H-like Mg xii only includes a fit to the \( n = 2 \) and \( n = 3 \) lines. (See Section 3.1 and Table 3 for details.) The purpose of the exercise is to demonstrate the importance of the higher order lines for establishing true \( N_j \) derivations, where fits to single lines (especially the \( n = 2 \) \( \alpha \)-transition which may lie on the saturated part of the COG) may give an \( N_j \) with possible values that span up to two orders of magnitude.
Figure 2. Velocity spectra obtained by co-adding the five strongest resonance lines for H and He like ions of nitrogen, oxygen, neon, magnesium, aluminium, silicon, and sulphur. For N, O, Ne, and Mg ions, MEG grating spectra are co-added, whereas HEG data are used for Al, Si, and S. We bin at 200 km s\(^{-1}\) in velocity; S is binned at 400 km s\(^{-1}\). Velocity bins are chosen to reflect the approximate FWHM resolution of the HETGS at the energies where these ions are found. To guide the eye, vertical lines denote velocities corresponding to 0, -1000 and -2000 km s\(^{-1}\). Multiple absorption components appear strongest for O, Ne, Mg, and Si. The errors are Poisson and each bin is independent despite appearances to the contrary.
3.3 The optical Hobby–Eberly 8 m spectrum

The flux calibrated HET spectrum of IRAS 13349 shown in Fig. 6 reveals a fairly typical quasar, where broad Balmer and Fe II emission lines and narrow [O III] emission lines are superposed on a blue continuum. Given the luminosity of IRAS 13349, any starburst component or contribution from the host galaxy is completely overwhelmed by the QSO emission.

As we did for the HST spectrum, we use SPECFIT to measure the emission lines and continuum in the HET spectrum. For the continuum we use a power law in $F_{\lambda}$. For the emission lines (excluding Fe II) two Gaussian components are needed to characterize the line profile. For H$\beta$ and the higher order Balmer lines, we tie the velocities and widths of all the components together. This is necessary and helpful in deblending these features from the ubiquitous Fe II emission. To fit the complex Fe II emission itself, we use the template derived by Véron-Cetty, Joly & Véron (2004) and convolve it with a Gaussian to match with the broadened component of the Fe II K$\alpha$ line.

Table 5 summarizes our measurements for each of the detected lines. Line widths have been corrected for the instrumental resolution by subtracting the resolution of 231 km s$^{-1}$ in quadrature from the fitted value. We also quote 2$\sigma$ upper limits for the Si IV transitions at the same velocities as the other detected components since these are useful in constraining the ionization state of the absorbing gas. The lines are slightly broader than the resolution of the L-mode gratings, with intrinsic widths that are consistent with the Doppler parameter of 100 km s$^{-1}$ found for the X-ray absorbers. Assuming $b = 100$ km s$^{-1}$, we obtain the ionic column densities given in the last column of Table 5. Since the intrinsic widths of the UV absorption features are not broader than $b = 100$ km s$^{-1}$, these column densities can be considered lower limits for Ly$\alpha$, N v and C IV. The highest velocity component, at $-950$ km s$^{-1}$, has roughly the same velocity as the bulk of the X-ray absorption. The lower velocity component, at $-75$ km s$^{-1}$, has a lower outflow velocity than most detected X-ray features.

![Figure 3](https://academic.oup.com/mnras/article/430/4/2650/1095269/binary/fig3.png)

**Figure 3.** The Chandra-HETGS spectra at $\sim$6 keV reveal two prominent emission lines, one due to Fe K$\alpha$ at rest energy 6.4 keV and another similarly strong line at $\sim$7 keV that may be identified with H-like Fe XXVI or Fe I K$\beta$ blended with a broadened component of the Fe I K$\alpha$ line.

Table 4. UV and optical emission lines in IRAS 13349+2438.

| Line       | $\lambda_{\alpha}$ (Å) | Flux $^b$ | Velocity $^c$ (km s$^{-1}$) | FWHM (km s$^{-1}$) |
|------------|------------------------|-----------|----------------------------|-------------------|
| Ly$\alpha$ | 1215.67                | 5.3 ± 0.1 | $-710 \pm 368$             | 3026 ± 150        |
| Ly$\alpha$ | 1215.67                | 10.2 ± 0.1| $-710 \pm 368$             | 10018 ± 140       |
| N v        | 1240.15                | 1.1 ± 0.1 | $-1130 \pm 138$            | 3189 ± 210        |
| N v        | 1240.15                | 2.0 ± 0.3 | $-1130 \pm 138$            | 10018 ± 140       |
| Si IV+O IV | 1400                   | 1.4 ± 0.2 | $-801 \pm 203$             | 2554 ± 360        |
| Si IV+O IV | 1400                   | 0.8 ± 0.4 | $-801 \pm 203$             | 7568 ± 730        |
| C IV       | 1549.05                | 2.6 ± 0.7 | $-1358 \pm 105$            | 2555 ± 360        |
| C IV       | 1549.05                | 5.7 ± 0.6 | $-1358 \pm 105$            | 7568 ± 730        |
| He II      | 1640.70                | 0.5 ± 0.3 | $-1358 \pm 105$            | 2498 ± 360        |
| He II      | 1640.70                | 1.8 ± 0.6 | $-1358 \pm 105$            | 7549 ± 730        |
| O IV       | 1663.48                | 0.3 ± 0.2 | $-1358 \pm 105$            | 2500 ± 154        |
| O IV       | 1663.48                | 0.1 ± 0.6 | $-1358 \pm 105$            | 7550 ± 730        |
| Al III     | 1857.40                | 0.4 ± 0.2 | $-891 \pm 500$             | 2174 ± 2190       |
| Si IV      | 1892.03                | 0.8 ± 0.4 | $-210 \pm 190$             | 1482 ± 360        |
| Si IV      | 1908.73                | 2.4 ± 1.3 | $-380 \pm 100$             | 2474 ± 590        |
| Si IV+Fe II| 4434–4684              | 3.2 ± 0.6 | $-318 \pm 100$             | 2130 ± 120        |
| Mg II      | 2798.74                | 6.5 ± 0.4 | $-318 \pm 100$             | 2130 ± 120        |

We note that the fits include the absorption lines, so there is no fitting bias that would artificially blueshift the centroids. Furthermore, the absorption lines are too weak to significantly impact fitting results even if unaccounted for.

$^a$Observed wavelengths are in vacuum for $\lambda < 3200$ Å and in air for $\lambda > 3200$ Å.

$^b$Observed flux in units of $10^{-14}$ erg cm$^{-2}$ s$^{-1}$.

$^c$Velocity is relative to a systemic redshift of $z = 0.10853$, the redshift of the [O III] $\lambda$5007 emission line.

In addition to these best-fitting parameters, we have made some empirical measures of the observed H$\beta$ profile and the Fe II emission for use in evaluating the mass of the central black hole in IRAS 13349 (Section 4.2.3) and for interpreting Eigenvector-1 (comprised of the relative equivalent widths of [O III] $\lambda$5007 and Fe II $\lambda$4434–4684 relative to H$\beta$) as described by Boroson & Green (1992). To measure the dispersion of the H$\beta$ profile directly from the data, we subtracted the fitted continuum, the fitted Fe II emission, and all other fitted emission lines from the original spectrum. We
then computed the empirical FWHM and the dispersion of this net spectrum over the 5266–5500 Å (4750–4962 Å, rest) wavelength range of the Hβ profile, to obtain FWHM = 2468 ± 4.7 km s$^{-1}$, velocity dispersion $σ_{Hβ} = 1948 ± 3.7$ km s$^{-1}$ and equivalent width $W_{Hβ} = 88.1 ± 4.5$ Å. (Note that the aforementioned Hβ values are derived using a more complex decomposition of the two components, i.e., a narrow core which dominates the empirical FWHM and a broader base needed to describe the Hβ line profile (see Table 4 and Fig. 6). Similarly, we subtracted the fitted continuum and all other emission lines from the original spectrum to obtain the observed Fe$^{II}$ spectrum. Integrated over the 4434–4684 Å rest-wavelength range as defined by Boroson & Green (1992), we obtain an Fe$^{II}$ flux of $3.41 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, and $W_{Fe^{II}} = 82.4$ Å. For [O III] λ5007 we obtain $W_{[O\text{ III}]} = 14.0$ Å. In the context of Eigenvector-1 and Eigenvector-2 characteristics as initially discussed by Boroson & Green (1992; see also Boroson 2002), IRAS 13349 behaves as a quasar at one extreme of the Eigenvector-1 correlations, e.g., the ratios O $\text{III}/Hβ = 0.22$, He $\text{II}/Hβ < 0.022$ and Fe $\text{II}/Hβ = 0.97$. Using the [O III] lines in IRAS 13349, we also update the redshift to $z = 0.10853 \pm 0.0001$. We note that the very high S/N HET spectrum enables the determination of the centroids of discrete spectral features to much better than a resolution element. For the sharp, bright [O III] λ5007 line, we can determine the centroid to an accuracy of 1.5 pixels corresponding to 30 km s$^{-1}$.

The strong Fe$^{II}$ and weak [O III] emission that characterize extreme Eigenvector-1 objects are common to Narrow-Line Seyfert 1 (NLS1) galaxies (e.g., see Pogge 2011 and Boroson 2011) and Véron-Cetty & Véron (2006) classify IRAS 13349 as an NLS1 based on its line width. However, our HET spectrum shows that IRAS 13349 does not satisfy two out of the three criteria primarily used to classify objects as NLS1s. The width of Hβ is too broad and exceeds the 2000 km s$^{-1}$ boundary, and the width of Hβ is also much broader than that of [O III] by nearly a factor of 3; NLS1s should have permitted and broad lines of similar width. Therefore, despite its extreme Eigenvector-1 characteristics, we do not consider IRAS 13349 to be an NLS1, in agreement with the determination of Grupe et al. (2004, 2010).

The HET and HST spectra are very similar to the prior observations of IRAS 13349. The continuum flux density is nearly identical to that observed by Will et al. (1992) and ~15 per cent brighter than that observed by Hines et al. (2001). Our emission-line fluxes are also comparable (but note that the units for the last column of table 3 in Hines et al. 2001 should be $10^{-14}$ erg cm$^{-2}$ s$^{-1}$), and agree to within 15 per cent for Hα. However, there are differences of 50–100 per cent for lines such as Hβ and [O III], which are badly blended with the optical Fe$^{II}$ multiplets. Although we have taken care to model explicitly the full Fe$^{II}$ emission spectrum, as have Hines et al. (2001), the fits can be highly model dependent, especially when one includes multiple components as we have for some lines (such as the Balmer lines, [O III], and [N II]). We suspect that the source of our differences in line fluxes are due to the methods used in deblending these features.

### 3.4 The infrared Spitzer IRS spectra

As shown in Fig. 7, the mid-IR continuum rises fairly smoothly to a peak of 0.8 Jy at 30 μm. Superimposed are weak, broad spectral features from silicate emission at 10 μm and 18 μm. Weak polycyclic aromatic hydrocarbon (PAH) resonances are also detected at 7.7 μm and 11.3 μm, indicating a weak starburst contribution to the mid-IR emission (Schweitzer et al. 2006; Shi et al. 2007).

![Figure 4](https://example.com/figure4.png)

**Figure 4.** HST/STIS low-resolution spectrum of IRAS 13349+2438 in observed wavelengths. Prominent emission lines are marked.

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Detail of the STIS G140L spectrum of IRAS 13349+2438, in observed wavelengths, in the Lyα region (top panel) and the C IV region (bottom panel). The black curves are the observed data; the red curves are the best fit to the spectrum. The emission features are labelled above the spectra, and absorption components are marked below. The ‘G’ labels denote foreground Galactic interstellar absorption lines.
The HET spectrum of IRAS 13349, in observed wavelengths, shows a typical quasar spectrum dominated by broad Balmer emission lines and [O III], with the exception of particularly strong Fe II. The lone absorption can be attributed to the atmospheric Franhofer B band which we have not corrected for, since it has no effect on the conclusions derived from our spectrum.

### 3.4.1 The low-resolution spectrum

We fit the low-resolution spectrum using the interactive data language (IDL) $\chi^2$-fitting routines MPFIT (Markwardt 2009),

 modified to include a silicate emission component.

The continuum model consists of six fixed-temperature blackbody dust emission components ($T = 25, 50, 100, 200, 300, 400$ K) and a blackbody stellar component (5000 K). The silicate emission is modelled as the product of a Galactic silicate opacity curve (Smith et al. 2007) and a blackbody dust emission component. The best-fitting temperature for the silicate emission is $\sim 200$ K. Adding additional temperature components did not improve the fit.

### Table 5. UV absorption lines in IRAS 13349+2438.

| Feature | No. of components | $\lambda_{\text{vac}}$ (Å) | $W_\lambda$ (Å) | $\Delta v$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | $\log N_{\text{col}}$ (cm$^{-2}$) |
|---------|-------------------|-----------------------------|-----------------|--------------------------|-------------------|-------------------------------|
| Ly$\alpha$ | 1 | 1215.67 | 0.59 ± 0.05 | $-72 \pm 112$ | 204 ± 19 | $14.20 \pm 0.06$ |
| Ly$\alpha$ | 2 | 1215.67 | 0.31 ± 0.11 | $-965 \pm 25$ | 270 ± 19 | $13.83 \pm 0.06$ |
| N V | 1 | 1238.82 | 0.23 ± 0.10 | $-159 \pm 308$ | 270 ± 19 | $14.09 \pm 0.16$ |
| N V | 2 | 1242.80 | 0.11 ± 0.10 | $-159 \pm 308$ | 270 ± 19 | $14.04 \pm 0.30$ |
| Si IV | 1 | 1393.76 | $<0.16$ | $-72$ (fixed) | 270 (fixed) | $<13.35$ |
| Si IV | 1 | 1402.77 | $<0.16$ | $-72$ (fixed) | 270 (fixed) | $<13.65$ |
| Si IV | 2 | 1393.76 | $<0.12$ | $-965$ (fixed) | 270 (fixed) | $<13.21$ |
| Si IV | 2 | 1402.77 | $<0.12$ | $-965$ (fixed) | 270 (fixed) | $<13.51$ |
| C IV | 1 | 1548.19 | 0.44 ± 0.24 | $-76 \pm 88$ | 309 ± 19 | $14.12 \pm 0.25$ |
| C IV | 1 | 1550.77 | 0.22 ± 0.12 | $-76 \pm 88$ | 309 ± 19 | $14.08 \pm 0.37$ |
| C IV | 2 | 1548.19 | 0.84 ± 0.17 | $-930 \pm 35$ | 309 ± 19 | $14.51 \pm 0.19$ |
| C IV | 2 | 1550.77 | 0.55 ± 0.14 | $-930 \pm 35$ | 309 ± 19 | $14.55 \pm 0.11$ |

$\Delta v$ velocity is relative to a systemic redshift of $z = 0.10853$.

$I$ Ionic column density assuming a Doppler parameter of $b = 100$ km s$^{-1}$.

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Figure 6. The HET spectrum of IRAS 13349, in observed wavelengths, shows a typical quasar spectrum dominated by broad Balmer emission lines and [O III], with the exception of particularly strong Fe II. The lone absorption can be attributed to the atmospheric Franhofer B band which we have not corrected for, since it has no effect on the conclusions derived from our spectrum.

Figure 7. The best-fitting model (green) to the low-resolution Spitzer IRS spectrum (× 1.077) showing all contributions (blackbody continua, silicate, PAH, starlight and narrow emission lines). In contrast, grey curve shows contribution from black bodies, starlight and silicate; additional contribution from PAH emission (blue) and narrow emission lines [S IV], [Ne II], [Ne III] and [O IV] (purple) are also shown. The model components contributing to the aforementioned include silicate emission (bottom, black) superimposed on a blackbody continuum (red) and hot dust or starlight (magenta; note that it is not possible to distinguish the two without observations at near-IR wavelengths). The best-fitting silicate emission temperature is $\sim 160$ K, while the continuum components have temperature range 50–400 K. (The T = 25 K continuum component has negligible contribution to the fit and hence not shown as part of the model here.)

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6 http://cow.physics.wisc.edu/craigm/idl/idl.html
### Table 6. Mid-IR emission lines in IRAS 13349+2438.

| Feature$^a$ | $\lambda_{\text{rest}}$$^b$ ($\mu$m) | $\lambda_{\text{vac}}$$^c$ ($\mu$m) | $W_d$$^d$ ($\times 10^{-3}$ $\mu$m) | FWHM$^e$ ($\times 10^{-2}$ $\mu$m) | Flux$^f$ ($\times 10^{-21}$ $\text{W cm}^{-2}$) |
|-------------|-----------------|-------------|-----------------|-----------------|-----------------|
| PAH(+H(?))  | 7.678 ± 0.007   | 7.700       | 4.91 ± 0.99     | 15.27 ± 0.10    | 11.87 ± 2.40    |
| [S IV]      | 10.506 ± 0.001  | 10.511      | 2.35 ± 0.14     | 4.61 ± 0.73     | 4.98 ± 0.23     |
| PAH(+H+He+Mg$^2$SO$_4$?) | 11.243 ± 0.001 | 11.250      | 5.14 ± 0.95     | 16.14 ± 0.09    | 7.97 ± 1.41     |
| PAH(+H(?))  | 12.686 ± 0.003  | 12.700      | 0.99 ± 0.31     | 2.47 ± 0.26     | 1.17 ± 0.37     |
| [Ne II]     | 18.219 ± 0.001  | 18.813      | 3.15 ± 0.40     | 3.10 ± 0.14     | 3.51 ± 0.48     |
| PAH(+H(?))  | 14.241 ± 0.006  | 14.250      | 3.24 ± 1.75     | 4.62 ± 0.82     | 1.04 ± 0.74     |
| [Ne III]    | 14.323 ± 0.003  | 14.322      | 2.96 ± 0.53     | 7.29 ± 0.39     | 3.30 ± 0.52     |
| [Ne III]    | 15.560 ± 0.002  | 15.555      | 3.39 ± 0.61     | 1.96 ± 0.13     | 2.48 ± 0.54     |
| [S III]     | 24.317 ± 0.009  | 24.318      | 4.65 ± 1.86     | 8.30 ± 1.02     | 2.23 ± 0.80     |
| [O IV]      | 25.906 ± 0.002  | 25.890      | 28.35 ± 3.10    | 5.92 ± 0.23     | 9.43 ± 1.16     |

$^a$Feature’s name.
$^b$Measured wavelengths (rest frame).
$^c$Laboratory wavelengths (vacuum).
$^d$Equivalent widths.
$^e$Full width at half-maximum.
$^f$Flux.

up to (and possibly exceeding) 400 K is indicated by the blackbody components of our continuum model. Keck optical interferometry at $K$ band suggests near-IR emission from an inner radius of 0.92 ± 0.06 pc (Kishimoto et al. 2009), reasonably consistent with dust at temperatures near sublimation. The peak of the SED (in $\nu F_{\nu}$) occurs at $\sim$20 $\mu$m, corresponding to a temperature of $\sim$200 K. However, with a clumpy dust distribution, the bulk of this dust emission may still come from a region close to the sublimation radius.

#### 3.4.2 The high-resolution spectrum

Dust signatures include a strong mid-IR excess and emission features pointing to PAHs. However, it should be noted that while we have identified the 11.2 $\mu$m feature with PAH, additional contributions from H and/or Mg-rich olivines (e.g. forsterite, Mg$_2$SiO$_4$; see Markwick-Kemper et al. 2007) are also a possibility. Detailed modelling to determine the relative contributions of PAH to Mg-rich olivines (if they exist in IRAS 13349) is beyond the scope of this paper, however.

In addition to dust features, low equivalent width, narrow-forbidden emission lines from a range of ionization states of O, Ne and S are detected (see Table 6 and Fig. 8). In particular, the [Ne v] and [O iv] lines originate from gas that is highly photoionized by the UV continuum from the active galactic nucleus (AGN). Moreover, the [Ne iii], [Ne ii] and [S iii] lines are likely dominated by AGN emission, although there may be contribution from star-forming regions.

Tommasin et al. (2010) presented a comprehensive mid-IR high-resolution spectroscopic survey of 91 Seyfert galaxies and derived useful observational and semi-analytical diagnostics that we also use here to assess the degree to which IRAS 13349 is AGN- or starburst-dominated. In particular, a good tracer of AGN contribution can be found in a comparison of the [Ne v]14.32 $\mu$m: [Ne ii]12.81$\mu$m ratio against [O iv]24.32 $\mu$m: [Ne ii]12.81$\mu$m. For IRAS 13349, these values are, respectively, 0.800 ± 0.223 and 2.958 ± 0.322, pointing to an 80–90 per cent AGN contribution to the IRAS 13349 IR emission, according to fig. 8 a of Tommasin et al.

![Figure 8.](https://academic.oup.com/mnras/article-lookup/doi/10.1093/mnras/stx2859)
Figure 9. Observed and intrinsic spectral energy distribution (SED) of IRAS 13349 based on our observations. The x-axis (both $\nu$ and $\lambda$) is in the rest frame. The solid points with error bars are archived data from (1) ISO 170 $\mu$m data from Spinoglio et al. (2002), as labelled, (2) IRAS 12, 25, 60 $\mu$m measurements of the IRAS Faint Source Catalog, Version 2.0 – Moshir et al. 1990 and (3) 2MASS Large Galaxy Atlas of Jarrett et al. 2003. Spectra are also shown (in solid black) of recent observations with the Spitzer IRS (IR), the HET (optical), the HST STIS (UV) and the Chandra HETGS (X-ray). The ‘composite QSO’ spectrum (solid green line) has been renormalized upward by 0.85 dex so that its EUV peak lies 0.25 dex above the IR peak of the observed IRAS 13349 spectrum, as is found in the mean RQ QSO spectrum of Elvis et al. (1994). The straight line segments between $10^{15}$ Hz and $10^{17}$ Hz show a range of simple assumptions for what the IRAS 13349 SED can be in the EUV energy range where there are no data. At one extreme, we take our observed SED without any corrections and decompose it into a set of power-law segments connecting the observed HST spectrum to the lowest ($\sim 0.3$ keV, rest) energy Chandra point (solid red). The solid blue line represents a ‘corrected’ UV spectrum where the ‘correction’ is derived by assuming that the intrinsic spectrum is represented by the composite QSO spectrum normalized to the observed HET spectrum of IRAS 13349 assuming a break at the peak of the composite spectrum (1000 Å rest) that we again extrapolate down to $\sim 0.3$ keV in the X-ray. The dotted blue line follows the continuum established by the composite spectrum renormalized by the relative UV and IR peaks of the Elvis et al. (1994) mean RQ QSO SED, which we again extrapolate through the EUV using a power law from the peak of the composite spectrum at 1000 Å to the Chandra 0.3 keV soft X-ray point.

4 THE IRAS 13349+2438 SPECTRAL ENERGY DISTRIBUTION AND ITS INFLUENCES ON THE WARM ABSORBER: OBSERVATIONS AND THEORY

In having considered the line detections separately in the different wavebands, here we assess the IRAS 13349 warm absorber based on photoionization modelling as tied to this QSO’s SED. In particular, we investigate the impact of different SED components (including the X-ray Compton power-law component, soft excess and big blue bump/accretion disc) spanning UV to X-rays on affecting warm absorber thermodynamic stability conclusions. We also investigate the methods for assessing the IRAS 13349 black hole mass and accretion rate based on the shape of the SED.

4.1 The observed spectral energy distribution of IRAS 13349+2438

To assess photoionization scenarios for the absorbing gas in IRAS 13349, we first need to know the intrinsic SED of the active nucleus that is illuminating the surrounding gas and dust. To start, we assemble an IR to X-ray SED based upon our observations and archival data (see Fig. 9). In the IR, we start with 170 $\mu$m far-IR Infrared Space Observatory Photometer (ISOPHOT) measurements (Spinoglio, Andreani & Malkan 2002), while mid-IR (12, 25 and 60 $\mu$m) IRAS data are taken from the Faint Source Catalog of Moshir et al. (1990) and near-IR photometric points are the Two Micron All-Sky Survey (2MASS) 1–2 $\mu$m data from the Large Galaxy Atlas of Jarrett et al. (2003). For comparison, we generate a ‘generic’ composite optical–UV QSO spectrum based on the Sloan Digital Sky Survey (SDSS) composite quasar spectrum of Vanden Berk et al. (2001) (for $\lambda > 3200$ Å rest) and the radio-quiet HST composite quasar spectrum of Telfer et al. (2002) at shorter wavelengths. If we normalize this composite spectrum to match our extinction-corrected HET spectrum...
at 5700 Å rest (resulting in the solid blue curve of Fig. 9; hereafter ‘5700 Å-normalized-generic-composite’) what immediately stands out is the large deficit of UV and far-UV flux in IRAS 13349, which is likely reradiated by heated dust in the IR since the observed SED peaks at 30 μm, rest. In the optical band, the HET spectrum of IRAS 13349 is virtually identical to that of the SDSS composite portion of the 5700 Å-normalized-generic-composite, indicating that the IRAS 13349 optical spectrum is only modestly reddened or extincted at these wavelengths. (The analysis of Hopkins et al. 2004 shows that the full SDSS composite has an internal Small Magellanic Cloud (SMC)-like extinction of $E(B-V) \sim 0.013$ at most.) The Balmer decrement measured in our HET data is 2.85 ± 0.18 for the ratio of Hα to Hβ. Correcting this for foreground extinction, it becomes 2.817 ± 0.18. To correct this to a nominal Case B value of 2.76 implies $E(B-V) = 0.021$ for an SMC-like extinction law. Comparing the Galactic-extinction-corrected spectrum of IRAS 13349 to the SDSS composite in more detail, the ratio (in the continuum) is flat from 4000–6000 Å; if anything, IRAS 13349 appears a bit bluer. So, internal extinction of the order of 0.01 to 0.02 (with an SMC-like law) is consistent with $E(B-V) = 0.021$ as derived from the Balmer decrement. For this value, $A_V = E(B-V) \Delta V_{R_V} = 0.09 \pm 0.02$ taking $R_V = 4.05 \pm 0.8$ ala Calzetti et al. (2000).

Based on the 5700 Å-generic-normalized-composite spectrum we find that the UV/optical peak (i.e. the peak of the solid blue SED) is 0.6 dex below the peak radiation in IR (at ~10^4 Å). According to the median radio-quiet QSO SED in fig. 12 of Elvis et al. (1994), the UV peak for a ‘normal QSO’ should be 0.25 dex above the IR peak. Assuming IRAS 13349 to be in this category (IR and optical spectra suggest this to be the case for IRAS 13349) its UV/optical peak is then 0.85 dex below that of an unabsorbed ‘normal QSO’. This suggests that either we are viewing the optical spectrum of IRAS 13349 through a grey screen or largely in scattered light, but from a scattering region that again is largely colour neutral at wavelengths longward of 4000 Å. At shorter wavelengths, the observed UV spectrum is likely some complex mix of scattered and absorbed light from the central regions. The complex geometry of this radiative transfer is difficult to unravel even using the added benefit of polarization information (W92; Hines et al. 2001), so to produce an SED that is fully corrected for these effects, we will assume that scaling the composite QSO spectrum to the level implied by the median QSO SED in Elvis et al. (1994) is a good representation of the intrinsic SED of the active nucleus of IRAS 13349.

The resultant SED (see Fig. 9, solid green and associated dotted blue line connecting it to the IR and X-rays) looks like a qualitatively good description for the intrinsic SED of IRAS 13349 since the extreme ultraviolet portion of the composite spectrum is declining smoothly to higher frequency in a way that would provide a good match to the soft X-ray portion of the spectrum observed with Chandra. Assuming this to be the intrinsic IRAS 13349 spectrum, at its corrected UV luminosity of $L_{2500} = 8.1 \times 10^{29} \text{ erg s}^{-1} \text{ Hz}^{-1}$, we derived $\alpha_\text{ox} = -1.83$, a value that is −0.25 lower than the nominal $\alpha_\text{ox} = -1.58$ value expected from the Young, Elvis & Rialliti (2010) relation. This slightly lower $\alpha_\text{ox}$ we observe for IRAS 13349 is consistent with the weak CIV absorption that we see in the HST spectrum (cf. Gallagher et al. 2006).

We have also checked the Elvis et al. SED against more recent compilations of QSO SEDs (Richards et al. 2006; Hopkins, Richards & Hernquist 2007; Shang et al. 2011) built from various combinations of SDSS, Spitzer, Far Ultraviolet Spectroscopic Explorer (FUSE) and HST data. The variation in the UV–IR peak difference (in log ($F_{\nu}$)) is less than a factor of 2 when comparing these different samples. (Note that the Hopkins et al. SEDs use the Richards et al. sample of objects but adds an additional $\alpha_\text{ox}$ correction based on the object’s peak UV flux; also, the Richards sample of QSO, in using primarily SDSS, has a median redshift $z > 0.5$.)

To assess luminosity contributions for the different waveband components of these SEDs, we integrate the line-segment SEDs of Fig. 9 over the energy bands noted in Table 7; we assume $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.25$ and $\Omega_\Lambda = 0.75$. These luminosities are then used as relevant for calculations in subsequent sections, either in whole or in part. The bolometric luminosity we derived from the piecemeal integration is $L_{\text{bol}} \sim 3.12 \times 10^{46} \text{ erg s}^{-1}$.

### 4.2 Reconstruction of the UV-to-X-ray SED and its components: theory and observations

The radiation from the central regions of AGN is likely to peak in the extreme ultraviolet at ~10–100 eV (~124–1240 Å), an energy range often suffering from extinction effects due to Galactic and/or intrinsic dust. As stated in Section 4.1, such is the case for IRAS 13349, which shows a large-UV and far-UV deficit in its observed SED, which we attribute to dust extinction, a conclusion also supported by Spitzer IR observations (see Section 3.4.1 for details). Likewise, the two most important spectral components featuring in this un-observable energy range are the disc blackbody from an

| SED | $L_{\text{bol}}$ | $L_{\text{IR}}$ | $L_{\text{opt}}$ | $L_{\text{UV}}$ | $L_{\text{EUV}}$ | $L_{\text{X}}$ |
|-----|----------------|----------------|----------------|----------------|----------------|---------------|
| 1°  | 1.42           | 1.19           | 0.72           | 0.36           | 0.68           | 5.55          |
| 2°  | 1.74           | 1.19           | 0.72           | 1.44           | 2.77           | 5.55          |
| 3°  | 3.90           | 1.51           | 3.72           | 9.73           | 9.89           | 5.55          |
| 4°  | 2.03           | –              | 1.95           | 9.60           | 7.19           | 5.42          |

*Observed SED – the solid red line in Fig. 9.
*Corrected SED – the solid blue line in Fig. 9 and in all panels of Fig. 10.
*Corrected SED – the dotted blue line in Fig. 9 and in all panels of Fig. 10.
*Theoretical SED – the solid red line in bottom panel of Fig. 10.
*Bolometric luminosity integrated from log $v = 11.5 – 20$.
*IR luminosity integrated from log $v = 11.5 – 14.5$.
*Optical (HET) luminosity integrated from log $v = 14.5 – 14.87$.
*Ultraviolet (HST) luminosity integrated from log $v = 14.87 – 15.5$.
*Extreme ultraviolet (unobserved) luminosity integrated from log $v = 15.5 – 17.0$.
*X-ray luminosity integrated from log $v = 17.0 – 20$. 

Table 7. Luminosity of IRAS 13349+2438 in different energy bands.
accretion disc peaking between 10 and 100 eV (typical of AGN) and the soft excess, typically manifesting at <1 keV. Here, using theoretical considerations in combination with our multi-waveband observations of IRAS 13349, we derive what we believe to be the most likely scenario for the intrinsic IRAS 13349SED, sans extinction.

The ionizing continuum dictating the ionization state of the absorbers in AGN is primarily contained in the UV-to-X-ray range. Therefore we focus our discussion on this energy range, with special attention paid to recreating the extincted UV part of the spectrum.

The general mathematical form we use in building the IRAS 13349 theoretical SED is

\[ f(ν) \sim \left[ A_{\text{pow}} ν^{\alpha - d} + A_{\text{se}} \right] e^{-\frac{ν}{ν_{\text{max}}}} \]

\[ + A_{\text{dbb}} f_{\text{dbb}}(ν, T_{\text{in}}) e^{-\frac{ν}{ν_{\text{max}}}}, \]

where the first and third terms in both equations (1a) and (1b) represent the 1–10 keV X-ray power-law and the big blue bump (modelled by ‘disc-blackbody’), respectively. As can be seen, the two equations differ only in the second term, associated with competing models describing the soft excess (see Section 4.2.1 for details). We proceed with a discussion of this component, to be followed by a more in-depth discussion of the big blue bump: its derivation and the dependence of its shape on the central black hole mass and accretion rate.

### 4.2.1 The sub-keV soft excess

Observations of most AGN reveal that the SED between 2 and 10 keV is well approximated by a power law with spectral indices \( \alpha \sim 0.9 \) (photon indices \( \Gamma \sim 1.9 \)). However, if this power law is extended to lower energies (<1 keV), for most type I AGN, there is additional unaccounted radiation, which has come to be known as the soft excess. This component is particularly important for shaping the nature of the X-ray absorber (Chakravorty et al. 2012). However, the physical origin of the soft excess is not understood, and presently the community largely treats it as a phenomenological spectral component modelled as a blackbody (equation 1a) with temperature \( T_{\text{se}} \sim 100–200 \text{ eV} \), which generally does a good job of describing most observations. Since this temperature is too hot for the temperature, \( T_{\text{in}} \), of the innermost stable circular orbit of the accretion disc in AGN (see equation 2), the soft excess is often believed to be a separate spectral component altogether or a reprocessed (shortward in wavelength) extension of the accretion-disc component. Our fit to the Chandra-HETGS spectrum of IRAS 13349 in Section 3.1 gives a temperature for the soft excess of \( T_{\text{se}} = 99 \text{ keV} \).

An alternative model \( f_{\text{se}}(ν) \) (equation 1b) for the soft excess is the thermal Comptonization model nthecomp (Lightman & Zdziarski 1987; Zdziarski, Johnson & Magdziarz 1996; Zycki, Done & Smith 1999) included in XSPEC v12.5 (Arnaud 1996). In this description, the seed photons from the accretion disc are reprocessed by the thermal plasma to generate sufficient photons at sub-keV energies to mimic the soft excess. The high-energy cut-off of this component is parametrized by the electron temperature \( T_{\text{e}} \) and the low-energy rollover is dependent on the effective temperature, \( T_{\text{in}} = T(R_{\text{in}}) \) (equation 2) of the seed photons from the accretion disc. Between the low- and high-energy rollovers, the shape of the spectrum is approximated by an asymptotic power law with photon index \( \Gamma_{\text{c}} \approx \frac{9}{8} ν^{-0.7} \), where \( y \) is the Compton y-parameter, which gives a measure of the extent of Compton reprocessing; i.e. the larger the value of \( y \), the greater the fraction of photons reprocessed from the accretion disc. For our modelling efforts, we adopt \( T_{\text{c}} = T_{\text{in}} = 100 \text{ eV} \), consistent with our Chandra soft X-ray data for IRAS 13349. The associated normalization constant \( A_{\text{se}} \) was determined from the ratio of the 35–5 Å (0.35–2.5 keV) photon flux in the soft excess component to that in the power law, as seen in the Chandra-HETGS data for IRAS 13349.

The aforementioned models of the soft excess do not influence the UV part of the spectrum and hence do not affect the predictions for the shape of the big blue bump (see Section 4.2.2). The soft excess is an important component influencing the ions which absorb the soft X-ray radiation. Our theoretical simulations show that there is a slight difference in the predicted ion fraction of the various soft X-ray ions, depending on the choice of models for the soft excess. However, while the Chandra-HETGS data cover the energy range of the soft excess, these are not sensitive enough to detect these relatively small differences in ion abundances, and hence cannot be used to differentiate between the nthcomp or blackbody models. Therefore, for the remainder of our analysis we adopt the nthcomp model with \( T_{\text{c}} = 2.3 \) and \( T_{\text{in}} = 100 \text{ eV} \), acknowledging that an alternative blackbody model with \( T_{\text{in}} = 100 \text{ eV} \) is likely to produce equally good results.

### 4.2.2 The ‘Big Blue Bump’

Multi-wavelength observations suggest that AGN continua peak in the EUV energy band and usually dominate the quasar luminosity (e.g. Elvis et al. 1994). This spectral component, often referred to as the ‘Big Blue Bump’, is considered to be the signature of the presence of an accretion disc. Yet, for many systems, it can only be partially observed in the UV–EUV energy range. As such, an attempt to reconstruct it requires careful theoretical considerations.

According to standard thin disc accretion theory (Shakura & Sunyaev 1973), radiation from the accretion disc may be modelled as a sum of local blackbodies emitted from the different annuli of the disc at different radii, the temperature of the annulus at radius \( R \) being

\[ T(R) = 6.3 \times 10^{3} \left( \frac{m_{\text{Edd}}}{M_{\odot}} \right)^{-\frac{1}{4}} \left( \frac{M}{10^{9} M_{\odot}} \right)^{-\frac{1}{4}} \left( \frac{R}{R_{\odot}} \right)^{-\frac{1}{2}} K, \]

(Peterson 1997; Frank, King & Raine 2002) where \( m \) is the accretion rate of the central black hole of mass \( M_{\text{BH}} \), \( m_{\text{Edd}} \) is its Eddington accretion rate and \( R_{\odot} \) is the Schwarzschild radius. The normalization constant \( A_{\text{dbb}} \) for this spectral component is given by

\[ A_{\text{dbb}} = \left( \frac{R_{\text{in}}/\text{km}}{D/(10 \text{ kpc})} \right)^{2} \cos \theta, \]

for an observer at a distance \( D \) whose line of sight makes an angle \( \theta \) to the normal to the disc plane. \( R_{\text{in}} \) is the radial distance of the innermost stable annulus of the accretion disc from the black hole. Thus, the radiation from the accretion disc has direct
dependence on the mass of the black hole and its accretion rate. As such, the shape of the SED can provide important diagnostic power for assessing the fundamental parameters of the black hole.

We acknowledge that more rigorous models exist for modelling the big blue bump, that involve real radiative transfer in the accretion disc (see e.g. Hubeny et al. 2000; Blaes et al. 2001; Hubeny et al. 2001; Hui, Krolik & Hubeny 2005) and/or the black hole spin effects (see e.g. Davis et al. 2005; Davis & Hubeny 2006). For the same black hole mass and accretion rate, relative to a simple 'disc-blackbody', these more-involved models change the location of the peak and the shape of the EUV spectrum, as UV and EUV flux get absorbed and re-emitted at longer wavelengths in these models. For models which include the black hole spin, the peak of the accretion-disc spectrum is pushed to higher energies for increasing black hole spin. Thus, qualitatively we can expect that using these models would result in higher black hole mass as compared to the best-fitting results obtained by using 'disc-blackbody', for the same accretion rate. However, since the UV spectrum of IRAS 13349 is heavily extincted, we cannot make observationally based distinctions between the different accretion-disc models. Given this, in the next section we opt for the less-computationally expensive 'disc-blackbody' model (Mitsuda et al. 1984; Makishima et al. 1986) to assess the mass and accretion rate of the black hole. While we present results based on fits to DISKB BB to allow for easier comparison to work on this and other AGN by other authors, we acknowledge that the model EZDISKB BB (Zimmerman et al. 2005) may be the theoretically more sound model and therefore also discuss our subsequent SED results based on a comparison of the two, where relevant. In brief, the major difference in the two models is most notable at R < 10R Gabriel, whereby the DISKB BB predicted temperature continues to increase in contrast to EZDISKB BB; this difference stems primarily from the EZDISKB BB imposed boundary condition that the viscous torque be zero at the inner edge of the disc.

4.2.3 Determining the mass and accretion rate of the IRAS 13349 black hole

Using the observed IRAS 13349 SED (see Section 4.1 discussion), in combination with equation (1), and the Shakura & Sunyaev (1973) model (applied to equation 1, third term), we generate a series of SEDs for different values of m and \( M_{BH} \) to obtain the best match to the IRAS 13349 SED (Fig. 9; Section 4.1 for details). We carry out an iterative, step-by-step approach to reconstruct the UV–EUV SED, with permutations of the relevant parameters, as described below.

We begin by running models using a coarse grid of various combinations of the parameter values \( m/m_{Edd} \) = (0.05, 0.1, 0.5, 1.0) and \( M_{BH} = (10^7, 10^8, 10^9) M_\odot \) for each \( m/m_{Edd} \), with a fixed \( R_\infty = 3R_g \). For this initial run, we find that \( m/m_{Edd} = 0.05 \) and \( M_{BH} = 9.0 \) gives a reasonable match to the observed IRAS 13349 SED (see the top-left panel of Fig. 10 comparing theoretical models with UV-composite QSO spectra, green data points). It should be noted that we can expect a range of acceptable matches between theory and observations for different permutations of key parameters, primarily due to the fact that equation (1), which we use for modelling the big blue bump, is degenerate between mass and accretion rate. The top panels of Fig. 10 demonstrate the effects on the shape of the theoretical SED when various combinations of \( R_\infty, M_{BH} \) and \( m/m_{Edd} \) are fixed/varied.

Therefore, to reduce uncertainties, we use a black hole mass derived from the \( \gamma \beta \) line width (\( \sigma_{25} = 1948 \pm 3.7 \text{ km s}^{-1} \); see Section 3.3) and the optical continuum luminosity \( \lambda L_{5100} = 6.28 \times 10^{44} \text{ erg s}^{-1} \), based on the renormalized, green-composite QSO spectrum in Fig. 9. Based on the McGill et al. (2008) relation,

\[
\log M_{BH} = 7.68 + 2 \log \frac{\sigma_{25}}{1000} + 0.518 \log \frac{\lambda L_{5100}}{10^{44}} \text{ erg s}^{-1},
\]

we derive for IRAS 13349, \( \log M_{BH} = 9.10 \text{ M}_\odot \); the McGill relation has an rms scatter in \( \log M_{BH} = 0.09 \). Barring better constraints, we use \( M_{BH} \sim 10^7 \text{ M}_\odot \) for input into equation (1) to determine the accretion-disc component of our theoretical intrinsic SED. Given that this \( M_{BH} \) estimate is close to our 'best-fitting' value from the initial coarse grid of runs based on a fixed \( R_\infty = 3R_g \), we next run a finer grid of models allowing all the aforementioned three parameters free. Fig. 10 (bottom panel) shows the best theoretical SED match (red curve) to the UV–EUV flux distributions based on our hypothesized extrapolation of observed data in the UV–EUV spectral domain (green points). The best match SED has optimal parameters \( M_{BH} = 10^8 \text{ M}_\odot, m/m_{Edd} = 0.2 \) and \( R_\infty = 10R_g \). Fig. 11 shows \( T_\alpha \) versus \( \log \alpha_{Edd} \) for all theoretical values of \( M_{BH} \), \( m/m_{Edd} \) and \( R_\infty \) that we have investigated, including where in these curves our best fits lie. For thoroughness, we also perform the same exercise using EZDISKB BB and find that while the 'best-fitting' SED shape remains the same, the same exercise with EZDISKB BB gives a higher accretion rate for fixed values of \( R_\infty \) and \( M_{BH} \). From our trials at finding the best match based on EZDISKB BB, the relevant SED parameters bracket a similar best range found using DISKB BB, i.e. \( 10^{8-9} < M_{BH} < 10^{2-3} \text{ M}_\odot, 0.2 \leq m/m_{Edd} \leq 0.7 \) and \( 3 < R_\infty < 10R_g \).

The shape obtained for the big blue bump is then complemented with X-ray power-law (Section 4.2), and soft excess (discussed in Section 4.2.1) components to derive the full UV–X-ray SED (Fig. 10 bottom panel – red) needed for input to photonization modelling. See luminosity information associated with SED 4 of Table 7. (Note that \( L_{Edd} \), which is primarily attributed to reradiation by dust that has absorbed part of the optical–UV radiation is excluded here, since it has no bearings on the actual disc spectrum.) Note that if the accretion-disc component is completely ignored and an SED is constructed on the basis of only the Chandra-HETGS X-ray data for IRAS 13349, then one would obtain the black dashed curve shown in the bottom panel of Fig. 10. Such an SED was used by Holczer et al. (2007) to study the warm absorber in IRAS 13349. In Sections 4.2.4 and 5.1, we discuss differences in and effects on derived absorber properties based on an ionizing SED that accounts for only X-ray contributions versus one which also includes disc contributions.

4.2.4 Advantages of using the full UV-to-X-ray SED for assessing the location(s) of the absorbing gas

Approximately half of all low-z AGN show high-ionization UV absorption lines and signatures of even higher ionization warm absorption in the X-ray data. In assessing the role of the disc ionizing radiation for affecting our conclusions on UV and X-ray warm absorber properties (e.g. common versus distinct origins; continuous versus clumpy clouds), we use XSTAR to generate ion fractions (Fig. 12) as a function of the temperature of the absorbing gas for the UV (panels A–C) and the X-ray (panels D–H) ions, using an SED that includes the big blue bump, the sub-keV soft excess and the X-ray power law (Fig. 10 lower panel – red curve) versus an
SED that only accounts for the X-ray spectral components, namely the power law and the blackbody soft excess, as determined from continuum fits to the X-ray data (Fig. 10 black dashed curve).

One of the most important ions in the X-ray warm absorber is He-like O VII. As can be seen in Fig. 12, its ion fraction is underpredicted by ∼25 per cent if the big blue bump is excluded from the ionizing continuum (panel D). The relative abundance of O VII and the H-like O VIII, another of the important ions in the X-ray warm absorber, are sensitively inter-related. Hence underprediction of the O VII ion would be associated with a complementary overprediction of the O VIII (panel G). Mg XI is also significantly overpredicted by an SED which excludes the big blue bump. Furthermore, it can be seen that the inclusion of the big blue bump predicts a larger ion fraction for the UV ions (panels A–C), and hence a higher likelihood that they are produced in the same gas as that responsible for O VII (panel-D) seen in X-ray absorbers. This is contrary to the conclusions one would arrive at, if considering an X-ray-only SED.

4.3 The ionized dusty absorbers in IRAS 13349

Using XSTAR 2.2.1, we generate ‘warm absorber’ models with ion populations that reflect the ionizing spectrum of our preferred IRAS 13349 SED (see Fig. 10, bottom panel, red SED; Section 4.2.3 for details). We employ the analytic version of XSTAR which enable line broadening and optical depth calculations in real time as relevant to the data. In addition, the granularity associated with analytic models are only in ξ, which we mitigate by creating population files sampled with Δ(log ξ) < 0.1. (In contrast, one can expect table models to have granularity in all free parameters – Tim Kallman, private communication.)

Using codes we developed for the ISIS (Houck & Denicola 2000) fitting/analysis package in combination with the aforementioned XSTAR-generated models, we initially fit the data (binned to the HETGS resolution) with nine absorber components spanning the −4 < log ξ < 4 range and find that it is the high-ξ (log ξ > 1) gas which drives the fit. Also in investigating dustless (Section 4.3.2)
and dusty (Section 4.3.3) absorption, we find that a statistically good fit describing the HETGS data (0.5–1.3 keV MEG and 1.2–8.9 keV HEG chosen to maximize both spectral resolution and throughput) is a power-law plus blackbody continuum absorbed by two ionized absorbers [hereafter WA-1 (log \( \xi \) = 1.68\( ^{+0.14}_{-0.16} \) log \( N_H = 21.03^{+0.05}_{-0.06} \)) and WA-2 (log \( \xi \) = 3.26\( ^{+0.05}_{-0.08} \), log \( N_H = 21.66^{+0.05}_{-0.06} \)) at similar (~700–800 km s\(^{-1} \)) velocities and iron dust (see Section 4.3.3 for details), intrinsic to the source. The reduced Cash statistic \( \Delta C \) for this model is 1.147 (2887.127/2540) and the corresponding reduced \( \chi^2 \) = 1.102 (2774.783/2540). While the fit naturally tend towards the aforementioned two-ab sorber+ dust model, we consider additional absorbers, driven by our own theory considerations based on thermodynamic stability arguments (see Section 5.1; also Section 4.3.1) and the detection of the UTA the previous XMM (Sako et al. 2001) study of IRAS 13349 (Section 4.3.2). While these additional absorbers aid in fitting a few additional weak lines, they do not add significantly to the overall improvement in fit statistics (\( \Delta C = 2842.34/2540 = 1.133, \chi^2 = 2741.884/2540 = 1.093 \)) for the addition of WA-3 and WA-4) – see Table 8 and Fig. 13 for details on the four-absorber+ dust model. We also test for the presence of additional absorbing material from within the Milky Way and find no strong evidence for its presence among the IRAS 13349 line of sight.

On the intrinsic IRAS 13349 absorption, Fig. 14 shows the observed and predicted column densities (\( N_j \)) of the various ions we have found in the UV and X-ray spectra of IRAS 13349+2438, based on both the plasma diagnostic approach of Sections 3 and the xstar photoionization fitting here. As demonstrated in the figure, the series fitting and xstar modelling agree with each other on the predicted column densities for many of the detected ions. For instance, it can be seen that for O\( vii \) (Fig. 14, left-hand panel A), the column density predicted from fitting the line series (horizontal shaded regions) matches with the xstar predicted \( N_j \). In addition, the figure is instructive in revealing the extent to which each absorber is responsible for the different ionic columns. Taking the example of O\( vii \) again, the dominant optical depth contribution comes from WA-1 and the \( N_j \) due to WA-2 falls short by 1.91 dex. On the other hand, for H-like Ne\( x \), Mg\( xi \) and Si\( xi \) (panels E–G) the higher ionization phase of WA-2 satisfies the observed optical depth due to the respective ion. In the following, we consider the impact of adding additional ionized absorbers.

### 4.3.1 A third warm absorber? – WA-3

It is interesting to note that the \( N_j \) for He-like Ne\( ix \) and Mg\( xi \) do not fall in the range predicted by either WA-1 or WA-2. This makes sense according to panels E and F of Fig. 12 which indicate that these ions peak at a temperature consistent with an ionization 2.0 < log \( \xi \) < 3.0. Indeed, theory considerations based on thermodynamic stability arguments (see Section 5.1 for details) point to more than two discrete zones of absorbers – when a third absorber (WA-3: log \( \xi \) = 2.98\( ^{+0.02}_{-0.05} \), log \( N_H = 2.30^{+0.05}_{-0.42} \times 10^{27} \)) confined within the ionization range dictated by our theory considerations (Section 5.1) is added to the fits, the aforementioned ions are better fit, although changes in fit statistics with the addition of this absorber is minimal (\( \Delta C = 1.143 \) (2872.129/2540) and reduced \( \chi^2 = 1.098(2759.126/2540) \)) – see Fig. 13 for ion contributions from WA-3. We will return to WA-3 in Section 5.1 in the context of...
As stated, our best model fit to the IRAS 13349 required a dust component for the X-ray fitting. For thoroughness, we investigate whether additional (gas phase) absorber components can take its place. In particular, L- to M-shell photoexcitations in lower charge states of Fe I to Fe XVI give rise to absorption at rest wavelengths 14–17.5 Å (≈0.7–0.89 keV), approximately the same spectral region where the dust absorption is required. These features, dubbed the UTA (see Behar, Sako & Kahn 2001 and Gu 2007 for theory), were initially detected by Sako et al. (2001) based on an XMM RGS study of IRAS 13349. To test for the prevalence and strength of these lines based on our method of analysis (i.e. one which tie line strengths to the observed UV–Xray ionizing SED), we explore fits which include additional absorber components that may account for them. (As a reminder, note that we began with an initial nine-absorber fit, covering the range −4 ≤ log ξ ≤ 4, that would have accounted for all UTA lines, if significant.)

We begin by checking the range of ionization parameters where the ion fractions of Fe I to Fe XVI peak (middle panel of Fig. 15). As can be seen in the figure, WA-(1–3) primarily account for the range of log ξ > 1.49, which while fitting for UTA ions Fe VII to Fe XVI, do not fully account for the Fe II to Fe XVI transitions that populate the spectral region between 17 and 17.5 Å (0.71–0.73 keV rest; observed ∼18.8–19.4 Å = 0.64–0.66 keV). Fig. 15 shows that the ‘missing’ low-ionization UTA lines should fall in the range −3.0 ≤ log ξ ≤ −1.0. As such, we include two additional warm absorber components: WA-4 (forced within −1.0 ≤ log ξ ≤ 1.0) and WA-5 (forced within −3.0 ≤ log ξ ≤ −1.0) to account for all ‘missing’ UTA producing ions. The resultant fits (WA-4: log ξ ≈ 0.99 with log N He II ≈ −1.78 and WA-5: log ξ ≈ −1.02; with log N O III ≈ −1.86) primarily affect O III to O VI with the strongest contribution to O IV (24.8 Å observed) and O IV (25.2 Å observed) absorption, while the fit statistics (ΔC = 1.138; X2 = 1.099) are still poorer than our best-fitting 4WA+ dust fit, although marginally. (See Section 4.3.3 for details on fitting for dust in X-ray spectra.) Indeed, as can be seen in Figs 14 and 15, WA-4 contributes noticeably to the column density for these lower ionization oxygen (K–M) and UV ions (H–J), while WA-5 give N values which are higher than those constrained by our HST measurements of Si IV and C IV. Nevertheless, this argues strongly for the UV and low-ξ X-ray warm absorbers 3–5 having similar origins, as also borne out based on kinematics (see Section 4.3.4). (For subsequent fits, we exclude WA-5 because it does not obviously contribute to the fits in a positive way.) It can be seen from Fig. 16 (blue) that the UTA alone cannot account for all the absorption in this spectral region.

4.3.3 Direct X-ray detections of iron dust

As just described, the UTA, while present, is unable to account for all absorption in the 17–17.5 Å (0.71–0.73 keV rest; observed ∼18.8–19.4 Å = 0.64–0.66) spectral region. It was initially proposed by Lee et al. (2001), based on a Chandra-HETGS study of the Seyfert galaxy MCG-6–30–15, that dust can be directly detected in high-resolution spectra of X-ray bright objects. For iron-based dust, these features appear in the form of Fe L (III, II, I) photoelectric edges between (lab) ∼14.7–17.5 Å (0.7–0.84 keV; overlapping with the UTA spectral region). (Fe-based dust in astrophysical environments can also be measured at ∼7 keV Fe K – see Lee & Ravel 2005, but this is not relevant to the Chandra-HETGS capabilities.) As can be seen in Fig. 16 (blue), the UTA is unable to account for much of the absorption between 19.3 and 19.5 Å (observed; ∼0.63–0.64 keV), consistent with the Fe L III edge (redshifted to zIRAS13349) – in the context of IRAS 13349, this argues strongly for direct detections of iron-based dust in the AGN environment.

To investigate the direct detection of iron-based dust in IRAS 13349, we incorporate cross-sections associated with condensed matter forms of iron into our four-absorber fit to determine an ionic column for iron in grains to be N Fedust ∼ (1.2 ± 0.21) × 10^{17} cm⁻². (See Lee et al. 2009 for details on X-ray methodology.)
for determining the quantity and composition of interstellar dust.) Using the interstellar medium (ISM) abundance values of Wilms et al. (2000), this translates to an equivalent hydrogen column \( N_H \sim (4.5 \pm 1.3) \times 10^{21} \text{ cm}^{-2} \). While the X-ray data are not of sufficient S/N ratio to distinguish the exact iron composition (e.g. pure Fe versus FeO versus Fe\(_2\)O \(_3\) versus Fe\(_3\)O\(_4\)), a conservative estimate of an observable transmission signal, requires that the iron-based grains have thickness \( t \sim 0.1-0.8 \mu\text{m} \), based on the formalism for transmission \( T = e^{-\tau_{\text{Fe}}} \), where \( \rho \) is the density of the specific compound as defined from ‘The Handbook of Chemistry and Physics’; the values for the attenuation length were obtained from the\(^8\) CXRO at LBL, and\(^9\) NIST. Furthermore, the fits strongly suggest that at least 90 per cent of the Fe is locked up in grains, with a minor contribution from gas phase iron, \( N_{\text{Fe-gas}} \sim 2.1 \times 10^{15} \text{ cm}^{-2} \).

### 4.3.4 The absorber kinematics

Of interest, the outflow velocities for the X-ray absorbers we detect are best matched to the higher velocity (\( \sim 950 \text{ km s}^{-1} \)) UV outflowing component – see e.g. Fig. 17 comparison of the HETGS view of \( \text{O VII} \) versus STIS view of \( \text{N V} \). Fig. 14 shows that the observed column densities for the UV ions \( \text{C IV} \) and \( \text{N V} \) (panels I and J) are consistent, within errors, with the \( \text{XSTAR} \) predicted column densities for the low-\( \xi \) phase of the warm absorber, determined from fitting to the \textit{Chandra} spectra (\( \text{O VII}, \text{panel N} \)). Our analysis shows that the low-\( \xi \) (WA-1 and WA-4) can have linked-UV and X-ray absorption from \( \text{C IV} \) to \( \text{O VII} \) and some \( \text{O VIII} \), although the latter is primarily associated with the higher \( \xi \) WA-2 and WA-3.

Furthermore, it would appear that the lower ionization phases are associated with a higher outflowing velocity. Our lower limits on the derived values for \( \nu_{\text{blue}} \) are roughly consistent with the upper limit findings by Sako et al. (2001; \( \nu_{\text{blue}} = 420^{+190}_{-180} \text{ km s}^{-1} \)) and Holczer et al. (2007; \( \nu_{\text{blue}} = 300 \pm 50 \text{ km s}^{-1} \)) if we account for the difference in choice of redshift value, i.e. \( z = 0.1074 \) (Kim et al. 1995) used by previous authors versus the \( z = 0.1085 \) value derived in this paper based on higher resolution HET data. We do not find any evidence for the \( \sim 20 \text{ km s}^{-1} \) outflow reported by Sako et al. however, and our fitted turbulent velocity widths are slightly lower than the \( v_{\text{turb}} \sim 640 \text{ km s}^{-1} \) values reported by both Sako et al. and Holczer et al.

### 5 DISCUSSION

#### 5.1 Thermodynamics and structure of absorber

A topic of active debate is whether warm absorbers in AGN are in a continuum medium or are an ensemble of discrete clumpy media which are in different thermodynamic phases in near pressure equilibrium with each other. The answer to this question has interesting consequences for the geometry of the AGN environment, as a whole. Here, we use stability curves to demonstrate that the choice of ionizing SED (e.g. X-ray versus the full source SED) for

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\( ^8 \) http://www.cxro.lbl.gov/optical_constants/

\( ^9 \) http://physics.nist.gov/PhysRefData/FFast/html/form.html
Figure 13. The best fit to the *Chandra*-HETGS spectrum of IRAS 13349 (in the observed frame). The numbers associated with the ion labels correspond to contributions from one or multiple absorbers as described in Section 4.3 and Table 8. Note that while this figure is shown with adaptive binning (15 counts bin$^{-1}$) to facilitate easier viewing, our fitting results are based on constant binning at the HETGS resolution. Only predicted lines with equivalent width $W_{\lambda} > 0.005$ mÅ are labelled.
IRAS 13349 is very relevant in the conclusion for one scenario over the other. Stability curves are thermodynamic phase diagrams of temperature (log $T$) versus pressure (log ($\xi/T$)), where $\xi = \text{ionization parameter}$. It is an effective theoretical tool often used to discuss the thermodynamics of photoionized gas associated with the X-ray and UV absorbers (e.g. Krolik, McKee & Tarter 1981; Reynolds & Fabian 1995; Krolik & Kriss 2001; Chakravorty et al. 2009, and the references therein). By definition, an isobaric perturbation of a system in equilibrium is represented by a small vertical displacement from the stability curve; such perturbations leave $\xi/T \sim L/nR^2$ constant, which for constant $L/R^2$ leave the pressure unchanged. Any ‘system’ located on the part of the curve with positive slope is a stable thermodynamic system, because a perturbation corresponding to an increase in temperature leads to cooling, while a decrease in temperature leads to the heating of the gas. If the stability curve is characterized with discrete allowed values of temperature at the same pressure, it points to a cloud-like absorber, whereas a wind-like scenario will have a continuous distribution of allowed temperature and pressure. Before proceeding, it is informative to briefly discuss the definition of the ionization parameter in the context of stability curves.

In the definition $\xi \sim L/nR^2$, it is conventional to use the luminosity $L$ in the energy range $13.6 \text{ eV} - 13.6 \text{ keV}$ (i.e. $1-10^3$ Rydberg). The warm absorber properties are, however, determined by the photon distribution in the soft X-rays ($E \gtrsim 100 \text{ eV}$) and not by photons with energy $E \lesssim 100 \text{ eV}$. Hence, in the making of warm absorber stability curves, authors often use modifications in the definition of the ionization parameter. For example, Chelouche & Netzer (2005, and references therein) use an ionization parameter $U_x$ which considers the ionizing flux only between $540 \text{ eV}$ to $10 \text{ keV}$. Chakravorty et al. (2012), on the other hand, simply normalize the stability curves by using the ratio of the total luminosity to the luminosity in the X-ray power-law component in the SED. However, it is to be noted that these modifications simply shift the entire stability curve along the log ($\xi/T$) axis and do not change the nature of the kinks or curves in the stability curve. For example, the range ($\Delta \log(\xi/T)$ or $\Delta T$) of the stable or unstable regions of the stability curves would remain unchanged with such modifications of the ionization parameters. As such, all the qualitative properties of the stability curves and comparisons between the stability curves of different SEDs, discussed subsequently, would remain the same even if better definitions of the ionization parameter are used.
In the context of AGN warm absorbers, several authors (e.g. Krolik et al. 1981; Gehrels & Williams 1993; Krolik & Kriss 2001) have commented that the gas in the $4.5 < \log T < 5$ region is thermally unstable, since the cooling function $\Lambda(T)$ has a negative gradient in this temperature range. As such, the ions detected on the stable regions of the stability curve bracketing this temperature range would be attributed to cloud-like absorbers where the different phases are in pressure equilibrium with each other. Based on the findings for just such an ionization gap in IRAS 13349 by Holczer et al. (2007) using data from the Chandra HETGS (the same data we are re-analysing in this paper) and Sako et al. (2001) with the XMM–Newton RGS, cloud-like clumpy absorbers would appear to be the conclusion one would draw for this quasar. (We note, however, that Sako et al. 2001 acknowledge that their stability curves do not show thermodynamically unstable regions for IRAS 13349.) In a comparison with the Holczer et al. (2007) results, the fact that their absorption measure distribution (AMD) methodology, despite assuming a continuous distribution of ions at the onset, concludes for thermodynamically unstable regions, further strengthens the case that is independent of fitting technique (e.g. AMD versus photoionization modelling as that employed here), it is the ionizing SED that is the critical factor.
values in the two curves, thus showing $\xi \sim T \sim \xi_{\text{HST}} \leq 10^9$ to model a spherical shell of solar metallicity gas.

In Fig. 18, it is theoretically allowed which is coincident with the aforementioned temperature range conventionally estimated to be unstable (negative slope) for photoionized gas in AGN environments. It can be seen that an X-ray only (disc free) ionizing SED leads to the prediction (black dashed curve) for a narrow range of $\xi$ coincident with the aforementioned temperature range over which the warm absorber is mildly unstable. Indeed, it is exactly the finding for ions on either side of this unstable phase seen in the black dashed curve that led Holczer et al. (2007) to their conclusions for IRAS 13349. In contrast, when we include the UV as part of the ionizing input, no such instability is seen, thereby pointing to a flow that is more wind like and continuous in IRAS 13349. The effect of the excess UV photons due to the addition of the accretion-disc component, facilitates the formation of $\text{O~vii}$ and other ions with similar ionization potential (see panel D of Fig. 12). $\text{O~vii}$ acts as a cooling agent and hence lowers the temperature of the gas, which results in thermodynamic stability in the region of WA-1. Moreover, the accretion-disc component also helps to lower the Compton temperature of the gas. Hence, the temperature of the curve in the region of WA-3 is lowered, rendering this part of the curve stable, as well. Thus, while our analysis reveals similar ionization states found from previous studies, the additional consideration of the UV influence drives us to a conclusion that the ionized absorber in IRAS 13349 should be more continuous and wind like than discrete clouds.

Taking the thermodynamic instability-free red curve in Fig. 18, it is interesting to further consider the conditions driving the fit results. Specifically, as discussed in Section 4.3, the components WA-1 and WA-2 are statistically ‘sufficient’ to fit the *Chandra*-HETGS data. However, there are no thermodynamic unstable phases between these two points to separate them – as seen in the figure (red curve). In other words, there is a range of $\xi$ which is theoretically allowed by thermodynamic calculations and yet is not required while fitting the data. While one explanation for this may be the insufficient S/N ratio of the available data, there may be additional more physically motivated answers. Specifically, (1) there may be an absence of absorbing material of sufficient column density at certain intermediate ionizations (which may be related to intermediate distances from the black hole) to imprint significantly on our spectrum. Indeed, for IRAS 13349, when we ‘force fit’ a third component WA-3 to the data, its physical conditions (log $N_{\text{Hii}}$ and $v_{\text{theo}}$) come out to be intermediate between that of WA-1 and WA-2. Furthermore, (2) when we include additional theoretically motivated component WA-4 and WA-5 to account for the entire UTA, we indeed populate the entire stability curve suggesting presence of material in a continuous distribution of ionization states. The stability conditions of a super-solar warm absorber would be distinctly different from that of a gas with solar abundances (see Chakravorty et al. 2009, 2012). Since the outflowing gas from the nuclear regions of AGN may indeed have super-solar metallicities (e.g. Arav et al. 2007), we explore this idea further for IRAS 13349 in the next section.

5.1.1 Super-solar metallicities

Chakravorty et al. (2009, 2012) show that the stability curves for a super-solar absorber is more likely to show discretely separated multi-phase structure. In Fig. 19, we show the stability curves for different super-solar metallicities of the absorber. Independent of whether only iron or all metals are varied, it can be seen that the higher metallicity gas starts exhibiting thermodynamic instability at log $T > 5.2$ and the high-ionization phase WA-2 (log $\xi \sim 3.4$; top-most, green circle) falls in a part of the curve after it recovers from this instability. However, there is no distinct unstable region between the low-WA-1 (log $\xi \sim 1.7$) and intermediate-WA-3 (log $\xi \sim 3$) ionization phases which would mean a continuous distribution of

**Figure 18.** Stability curves illustrating differences in the thermodynamic behaviour of the absorbing gas as illuminated by the full UV–X-ray SED (solid red curve corresponding to the SED in solid red shown in Fig. 10, bottom panel) versus a X-ray only ionizing SED (black dashed curve corresponding to the same representation of ionizing SED in Fig. 10, bottom panel). The unstable regions identified by the Holczer et al. (2007) analysis of this *Chandra* X-ray data based on an X-ray only ionizing SED is highlighted in bold black. Also in bold on the red curve is the aforementioned unstable region translated over the same $\Delta T$ for the stability curve drawn based on a UV (i.e. accretion disc) inclusive SED. The filled circles on the red curve are the points corresponding to WA-1, WA-2, WA-3, WA-4 and WA-5 as predicted by the *xstar* fits to the *Chandra*-HETGS data and the *HST* STIS data and/or theoretical considerations, as discussed in Section 4.3. As can be seen, no unstable regions are identified by our analysis. The dotted blue lines connect the points with the same $\xi$ values in the two curves, thus showing that the temperature for all the $\xi$ values are higher for the gas ionized by the X-ray only SED, except for WA-5, where the temperatures are equal.

Reynolds & Fabian (1995) and Chakravorty et al. (2012) discuss and demonstrate that a moderate to strong soft excess component makes the stability curve more stable at 10$^5$ K (see also Krolik et al. 1981). Chakravorty et al. (2012) further demonstrate in general for AGN that the inclusion of the accretion-disc spectral component in the EUV range in addition to a significantly strong soft excess may completely remove the apparent thermal instability in the aforementioned temperature range. In this paper, we revisit the conclusions for the thermodynamic stability conditions for the IRAS 13349 warm absorber gas in the context of different SEDs: one that excludes the disc components (mentioned X-ray studies of IRAS 13349) and one which includes them (this paper). For our simulations of the photoionized gas thermodynamic properties, we used *xstar* to model a spherical shell of solar metallicity gas having $N_{\text{Hii}} = 5 \times 10^{21}$ cm$^{-2}$ and particle density $n_e = 10^{6}$ cm$^{-3}$, illuminated by the aforementioned SEDs. It should be noted that the stability curves are insensitive to the choice of $10^{3} \leq n \leq 10^{12}$ cm$^{-3}$ for the IRAS 13349 ionizing spectra. It can be seen from Fig. 18 that the choice of ionizing spectrum strongly influences the conclusions for gas thermodynamic stability. For the two curves shown, we use thicker lines to highlight the temperature range conventionally established to be unstable (negative slope) for photoionized gas in AGN environments.
Figure 19. Stability curves corresponding to super-solar gas of $3Z_\odot$(blue), $5Z_\odot$(pink), $7Z_\odot$(black) and $9Z_\odot$(green), where (left-hand panel) $Z_\odot$ refers to all Z elements and (right-hand panel) $Z_\odot$ refers only to iron, i.e. only iron abundance are altered here. For comparison, in both panels, solar abundance stability curves are shown in solid red and plotted points correspond to XSTAR predicted ionization phases for the warm absorber.

5.2 The IRAS 13349 dusty warm absorber

Given the Reynolds (1997) finding back in the ASCA era that $\sim$20 per cent of the warm absorber Seyfert 1s have significant optical reddening, it is not surprising that there is now a remarkable convergence of evidence for dusty ionized winds from observations with more powerful satellites. That IRAS 13349 harbours dust has long been established with IR (Beichman et al. 1986; Barvainsis 1987), UV/optical (Wills et al. 1992; Hines et al. 2001) and X-ray (Brandt et al. 1996; Brandt et al. 1997) studies. Using the superb multi-wavelength data set presented here, in combination with knowledge based on prior work, we present a geometrical model for the IRAS 13349 line of sight (LOS) and location of dust, based on dust modelling of the absorbed optical–UV spectra (Section 5.2.2) and direct IR and X-ray measurements (Section 5.2.3) of dust properties.

5.2.1 A model for the IRAS 13349 dust

As we showed in Section 4.1, the direct UV and optical flux from IRAS 13349 is substantially lower than would be expected for a typical QSO. Additionally, the high polarization rising to shorter wavelengths (Hines et al. 2001) is indicative of scattering by dust. Hines et al. (2001) attempted to model the UV/optical flux and polarization of IRAS 13349 as a combination of a direct view of the nucleus reddened by an intervening screen, plus dust-scattered light from biconical regions filling the poles above the obscuring torus. Using dust with SMC-like properties, they were able to obtain a reasonable match to the shape of the polarized flux spectrum, but the predicted total flux spectrum did not match the observations – the optical flux was too much high, and the reddening caused the predicted UV flux to drop far below the observed intensity. When one also considers the shorter wavelength data from STIS presented in this paper, the fact that the UV flux is much higher than predicted by their model suggests that there could be additional scattering that is colour neutral, e.g. like the Thomson mirror of hot electrons in NGC 1068 (Antonucci & Miller 1985). This idea is reminiscent of the original suggestion by Wills et al. (1992) that the polarized light in IRAS 13349 was due to Thomson scattering, although that idea proved inconsistent with the wavelength dependence into the near-UV observed by Hines et al. (2001). For our proposed geometry here, the Thomson-scattered component would play a minor role in the polarization and only account for the flux at the shortest wavelengths.

To test this idea, we developed a simple heuristic model as illustrated in Fig. 20. As shown in the figure, our direct LOS (the dash–dotted line) to the active nucleus passes through the upper atmosphere of the obscuring torus. The atmosphere consists of a mixture of highly ionized gas and dust that has not yet been evaporated by the incident radiation. This LOS is heavily reddened in the UV/optical band, or even completely blocked; in the X-ray, since the gas is highly ionized, there is little absorption by lighter elements, and the active nucleus is visible (Brandt et al. 1997). A second...
LOD (the solid line and the dashed line) passes through less-dense portions of the atmosphere that are more transparent at UV/optical wavelengths, but this LOS only gives a view of the active nucleus as reflected by dust from the far wall of the obscuring torus. Finally, a third LOS passes above the atmosphere of the torus and it has a view of the nucleus that is Thomson-scattered from hot electrons in the thermal wind escaping along the polar cavities of the torus.

Assuming that the active nucleus plus broad-line region (BLR) has a spectrum identical to the composite QSO spectrum (defined as $f_c$), this model can be analytically expressed as

$$F_{\text{opt/UV}}(\lambda) = [F_{\text{direct}}(\lambda) + F_{\text{scat}}(\lambda) + F_{\text{Th}}(\lambda)] \times 10^{0.4A_V(\lambda)}, \quad (5)$$

where $A_V$ is the optical absorption within our Galaxy and $g(\lambda) = A_g / A_V$ is the extinction law in the Milky Way, as defined by Fitzpatrick (1999). The other components within the IRAS 13349 galaxy are the following.

(i) Absorbed direct flux in the torus, torus atmosphere and galaxy. We define the LOS flux passing directly through the torus by

$$F_{\text{direct}}(\lambda) = \Gamma_d f_c(\lambda) \times 10^{0.4(A_{\text{V,int}} + A_{\text{V,atm}} + A_{\text{V,gal}} + A_{\text{gal}}(\lambda))}, \quad (6)$$

where $\Gamma_d$ is the absolute normalization of the composite spectrum, $A_{\text{V,int}}$ and $g_{\text{int}}(\lambda) = A_{\text{V,atm}} / A_{\text{V,int}}$ are the optical absorption and the wavelength-dependent extinction law within the torus, $A_{\text{V,atm}}$ and $g_{\text{atm}}(\lambda) = A_{\text{V,gal}} / A_{\text{V,atm}}$ are the optical absorption and the wavelength-dependent extinction law within the torus atmosphere and $A_{\text{V,gal}}$ and $g_{\text{gal}}(\lambda) = A_{\lambda_c}/A_{\text{V,gal}}$ are the optical absorption and the wavelength-dependent extinction law within the galaxy, respectively.

(ii) Absorbed dust-scattered UV/optical flux in the torus atmosphere and diffuse medium.

$$F_{\text{scat}}(\lambda) = \gamma_{\text{scat}} \Gamma_d f_c(\lambda) \left(1 + \frac{\lambda}{\lambda_c}\right)^{-\alpha} \times 10^{0.4(A_{\text{V,atm}} + A_{\text{V,gal}} + A_{\text{gal}}(\lambda))}, \quad (7)$$

where $(1 + \lambda / \lambda_c)^{-\alpha}$ stems from the wavelength dependence of the scattering ($\alpha = 4$ is the Rayleigh limit), $\lambda_c$ is the critical wavelength of the scattering, characteristics of the typical dust grain size and $\gamma_{\text{scat}}$ is the fraction of direct light which is dust-scattered.

Figure 20. Inferred geometry of IRAS 13349. See Section 5.2 for details.

(iii) Absorbed Thomson-scattered UV/optical flux in the diffuse medium.

$$F_{\text{Th}} = \gamma_{\text{Th}} \Gamma_d f_c(\lambda) \times 10^{-0.4A_{\text{V,gal}} g_{\text{gal}}(\lambda)}, \quad (8)$$

where $\gamma_{\text{Th}}$ is the fraction of direct light which is Thomson-scattered.

5.2.2 The wavelength-dependent extinction within IRAS 13349

With this model in mind, we consider, through $\chi^2$ fitting, which combination of dust absorption and scattering best describes the IRAS 13349 observed optical–UV spectrum. We used the Levenberg–Marquardt minimization to determine goodness of fit, based on the IDL code MPFIT (Markwardt 2009). However, we do not have any information about the extinction within IRAS 13349, neither in the galaxy nor in the torus and torus atmosphere. We therefore considered several permutations of existing laws previously published for the MW (Fitzpatrick 1999), the average SMC and Large Magellanic Cloud (LMC) (Gordon et al. 2003) and starburst galaxies (Calzetti et al. 2000). The worst fits were obtained with the MW and/or LMC extinction, due to the presence of the 2175 Å bump in these laws. This points towards IRAS 13349 lacking the unknown dust population responsible for this 2175 Å absorption feature in the MW and the LMC, in good agreement with several studies showing that the dust content in AGNs is SMC-like (see e.g. Crenshaw et al. 2001; Hopkins et al. 2004, and references therein). As expected, the use of the SMC and/or the Calzetti laws gives better results, but the fits are still poor, with reduced $\chi^2 \geq 3$.

We therefore build our own SMC-like extinction laws for the IRAS 13349 torus, torus atmosphere and galaxy as

$$g_{\text{int}}(\lambda) = \left(\frac{5448}{\lambda}\right)^{\beta_{\text{int}}} \quad (9)$$

in the torus,

$$g_{\text{atm}}(\lambda) = \left(\frac{5448}{\lambda}\right)^{\beta_{\text{atm}}} \quad (10)$$

in the torus atmosphere and

$$g_{\text{gal}}(\lambda) = \left(\frac{5448}{\lambda}\right)^{\beta_{\text{gal}}} \quad (11)$$

in the galaxy. These laws are built so that they are equal to one in the $V$ band, and we assume that the dust population is different in the torus, the torus atmosphere and the rest of the galaxy. In our fit, the spectral indices $\beta_{\text{int}}, \beta_{\text{atm}}$ and $\beta_{\text{gal}}$ are free parameters along with the optical extinction within the torus $A_{\text{V,tor}}$, the atmosphere $A_{\text{V,atm}}$ and the galaxy $A_{\text{V,gal}}$, the fraction of dust- and Thomson-scattered light $\gamma_{\text{scat}}, \gamma_{\text{Th}}$ and the critical dust-scattering wavelength $\lambda_c$. The absolute normalization of the composite spectrum $\Gamma_d$ is fixed to the level discussed in Section 4.1, the dust-scattering spectral index $\alpha$ is fixed to four (Rayleigh limit), and the optical extinction within the MW is fixed to $A_{\text{V,gal}} = 0.04$ in the manner of the Wills et al. (1992) derived value for IRAS 13349.

(i) Best-fitting dust model. In our fitting, we are unable to constrain the fraction of dust-scattered light $\gamma_{\text{scat}}$ as it systematically pegs to one. We can interpret this as due to (1) an overestimation, by the composite spectrum, of the nucleus continuum in the optical or (2) the presence of another contributing component in the optical domain. We therefore fix $\gamma_{\text{scat}} = 0.2$, a conservative value chosen...
As detect iron-based dust in the μ ∼ IRS, erg s ∼ 0.02 Optical extinction in atmosphere (d.o.f) 1.66 (862) 0.003 Fraction of Thomson-scattered light HETGS and ∼ 1500 0.024 X-ray and IR measurements, although the conclusions based on our polarization-free fits are consistent with those of Hines et al. (2001) based on polarization studies. Specifically, Hines et al. showed that polarization is wavelength dependent, therefore pointing to dust-scattering dominating over wavelength-independent Thomson-scattering. Similarly, our fits point strongly to dust-scattered light dominating the 2000 and 8000 Å spectral region.

5.2.3 Direct X-ray and IR measurements of the IRAS 13349 dust

Using additional knowledge gained from direct X-ray and IR measurements of the IRAS 13349 dust properties as enabled by the superb spectral resolution of the Chandra HETGS and Spitzer IRS, we further consider the location of the different composition grains we detect.

(i) Chandra X-ray spectroscopic detection of iron grains. As described in Section 4.3.3, we directly detect iron-based dust in the X-ray corresponding to NiFe abundances = (4.5 ± 1.3) × 10^{15} cm^{-2} and grain size ∼ 0.1−0.8 μm. According to the radiative transfer calculations of Kama, Min & Dominik (2009), iron sublimes between ∼ 1000 and 2700 K as a strong function of densities (i.e. pressures). The protoplanetary disc conditions that they consider have typical vapour densities of ∼ 10^{12}−10^{10} g cm^{-3} which translate to particle density ∼ 10^{10}−10^{12} atoms cm^{-3}, assuming 55 g mole Fe^{-1}, not dissimilar to the particle densities that one would expect for the inner AGN clouds. More importantly, at these densities, iron sublimes at 1400 K, a higher temperature than silicates at 1100−1300 K. As such, in the context of our geometrical model for the IRAS 13349 viewing geometry (Fig. 20), we can place the iron in the upper, less optically thick layers of the torus atmosphere, with the silicates more towards the interior. Furthermore, in adopting the formalism

\[ R_3 \simeq 0.4 \left( \frac{L}{10^{45} \text{ erg s}^{-1}} \right)^{1/2} \left( \frac{1500 K}{T_{\text{sub}}} \right)^{2.6} \text{ pc} \]  

derived by Nenkova et al. (2008), we find ∼ 2.7–5.2 pc for the inner radius of cloud distributions in a clumpy torus for sublimation temperatures T ∼ 1100–1400 K and L_{bol} ∼ 3 × 10^{46} erg s^{-1} (see Table 7). The Keck Interferometer measurements of Kishimoto et al. (2009) point to dust at ∼ 92 pc, which suggests either dust T ∼ 2000 K or larger dust grains (e.g. 1.2 μm as derived based on spectral fitting in Section 5.2.1) – see also (e.g. Sitko et al. 1993).

(ii) Spitzer IRS spectroscopic detection of silicates and PAHs. As discussed in Section 3.4, the Spitzer IRS spectra show weak 7.7 μm and 11.3 μm PAH, as well as broad 10 μm and 18 μm silicate emission. The PAHs are associated with the outer star-bursting part of the galaxy and therefore play no role in the dust absorption and scattering effect considered previously. Even if the obscuration is a supernova-heated starburst disc (see e.g. theory in Fabian et al. 1998; Wada & Norman 2002; Thompson, Quataert & Murray 2005; Ballantyne 2008), in the IRAS 13349 host galaxy, any PAHs will have to be far enough away from the strong radiation to have little effect. Else, for the detected silicates, given that they are in emission, just like in other normal quasars and Seyfert 1s, it is quite clear that we are not looking through a lot of dust, but rather are at a high-enough elevation angle above the torus to clear the densest gas, but perhaps just grazing the surface and looking through its atmosphere, which is what is causing the UV and X-ray absorption lines and the extinction of the UV continuum.

Furthermore, the 10 μm peak is shifted to the red, indicating either a depletion of small dust grains or more crystalline silicate

![Figure 21. Best-fitting model for the UV/Optical spectrum of IRAS 13349 (observed-spectrum in grey). The full modelled spectrum is the red line. The Thomson-scattered component is the green line and the dust-scattered component is the blue line. We also include the polarized light (magenta) as measured in Hines et al. (2001). Our fit results point to the direct light having marginal contribution, pointing to almost complete obscurcation by the torus in the UV and optical.](https://academic.oup.com/mnras/article/430/4/2650/1095269)
dust (e.g. enstatite) rather than amorphous olivine. The opacity at the 1.844 keV (6.724 Å, rest) Si K edge is too low for us to verify the type of silicates with X-ray data. However, the fact that the dust we do detect in the X-rays is primarily locked up in iron, argues strongly for the silicates to be Mg rich (e.g. forsterite). Markwick-Kemper et al. (2007) argue for forsterite in the PG 2112+059 broad absorption line QSO wind based on Spitzer studies; one might imagine a similar dusty outflow for IRAS 13349, but as stated in Section 3.4.2, assessing the level forsterite may contribute to the 11.2 μm feature is beyond the scope of this paper.

In further estimating where the silicate dust responsible for the broad IR emission may reside, we derive \( R_{\text{sub}} \sim 1.2 \) pc, using the relation \( R_{\text{sub}} = 0.2(L_{\text{bol}}/10^{46})^{1/2} \) pc (Laor 1998, 2003). To arrive at this, we take the mid-IR luminosity of IRAS 13349 \( \nu L_\nu (25 \mu\text{m}) = 3.2 \times 10^{45} \) \( L_{\text{bol}} f_L \) erg s\(^{-1}\), where \( f_L \sim 0.6 \) is a representative dust covering fraction and \( f_L \sim 0.5 \) is a representative mid-IR anisotropy for quasars (Shi et al. 2005; Ogle, Whyssong & Antonucci 2006). Based on this, it is likely then that the dust responsible for the mid-IR continuum is the same dust that absorbs the direct optical–UV spectrum, since it accounts for a large fraction of the absorbed and reprocessed bolometric luminosity of the quasar.

### 5.3 The dusty wind in IRAS 13349: torus or accretion-disc origin?

Given the excellent qualitative agreement between our proposed model for the dust contributions (Section 5.2.2) and the observed spectrum, our picture in Fig. 20 must be close to reality. One additional piece of evidence in support of our model can be gleaned from the existing polarization data. Hines et al. (2001) note a difference in polarization angle for the broad emission lines compared to the continuum. The line centres have their angles rotated by \( 5^\circ \), but the polarization stays fairly constant. One can interpret this rotation in terms of the differing angle between the scattering region and the sources of the incident radiation, meaning that the BLR is displaced from the optical/UV continuum source by several degrees as viewed from the scatterer. Also, since the emission lines are not depolarized, the angles from across the full BLR to the scatterer must be within a fairly narrow range so that their polarizations do not cancel out. So, the size of the BLR as seen from the scatterer must be small. If we take the difference in polarization angle as the offset of the BLR from the continuum source, then, given a distance for the BLR from the nucleus, we can deduce the distance of the scatterer from the continuum source. Scaling up reverberation mapping results for BLR sizes (Kaspi et al. 2005) to our extinction-corrected UV luminosity for IRAS 13349 \( L_{1550} = 7.95 \times 10^{43} \) erg s\(^{-1}\), the BLR would be at a radius of \( r = 7 \times 10^{15} \) cm. The scatter would then be at \( 8 \times 10^{18} \) cm or 2.6 pc. For comparison, the dust sublimation radius \( R_{\text{sub}} \sim 1.2 \) pc we calculate in Section 5.2.3 (same value from Barvains 1987), and the inner edge of the torus is expected to be at \( \sim 28 \) pc (Krolik & Begelman 1988). This is remarkably consistent with the optical light being scattered light from the far wall of the torus. In adopting the classic picture presented whereby an obscuring torus is always present (Antonucci 1993; see also Lawrence & Elvis 1982) our view of IRAS 13349 then is at high inclination, barely skimming the surface of the torus.

This picture presents a problem then for scenarios of accretion-disc winds (e.g. Elvis 2000), where the wind streamlines favour the equatorial plane, parallel to the surface of the torus. Nevertheless, it is of interest to consider further an alternative to the torus for the obscuration, that would allow the wind to have an accretion-disc origin. Recently, Czerny & Hryniewicz (2011) proposed a model for the creation of dusty winds at \( \gtrsim 1000 \) km s\(^{-1}\) by drawing parallels between clouds on quasar disc surfaces to similar temperature and pressure conditions that cause dust formation in AGB stars. In the context of the Elvis quasar model, the material in this wind would then be the cause of the obscuration, in lieu of the torus. But can this satisfy our condition for a high inclination viewing angle for IRAS 13349? Based on the wind-flow lines shown in fig. 3 of Risaliti & Elvis (2010), the scale height at which our LOS intersects the dusty wind is \( z = 200 R_3 = 0.09 \) pc at \( 1000 R_1 \) for a \( 10^7 M_\odot \), close to the disc plane. Alternatively, a warped disc as the source of obscuration (Lawrence & Elvis 2010), although for IRAS 13349, would have to be contorted in such a way so as to satisfy the known effects caused by dust-scattering, absorption and polarizing. Else, if we again consider the putative torus, one might argue that our LOS on the near side of the torus passes under the streamlines of the accretion-disc wind, but then the LOS from the nucleus to the far wall of the torus and back again must pass directly through the wind, and at multiple angles.

While the accretion-disc wind idea is a desirable one, it is ultimately more difficult to reconcile, compared to a torus wind, for IRAS 143349. The line widths in our STIS spectrum are similar to the narrow, few hundred km s\(^{-1}\) absorption lines common in other nearby AGN (Kris 2002; Crenshaw, Kraemer & George 2003; Dunn et al. 2007), as expected for the thermal winds of Krolik & Kris (1995, 2001). Also, the velocity shifts we detect in both UV and X-ray are slow compared to the ultra-fast outflows expected from the disc (Tombesi et al. 2010; see also Chartas et al. 2002; Pounds et al. 2003 for the first claims of such outflows in Seyferts).

If there is no disc wind in this object, then perhaps the conditions that drive it are just not right. The disc winds of Murray et al. (1995); Murray & Chiang (1995) require a high ionization parameter and a high column density at the inner edge of the wind, and IRAS 13349 does not have a high column density of either X-ray or UV-absorbing gas. The manifestation of a disc wind in an AGN may not be a universal property that depends only on orientation, but also on other intrinsic parameters such as the accretion rate or the Eddington ratio.

### 5.4 Similarities to non-black hole astrophysical systems

It is interesting that many apparent parallels can be drawn between IRAS 13349, a massive energetic black hole systems fuelling a whole galaxy and other less powerful/smaller systems. For example, the relatively large grains found in the torus of IRAS 13349 are also encountered in the dusty winds of luminous blue variable (LBVs, see e.g. Robberto & Herbst 1998; O’Hara et al. 2003). In these extreme massive stars, the maximum grain size is set proportionally to the mass-loss rate of the high-opacity wind, and dust is likely created during stellar eruptions, when this mass-loss reaches very high levels (0.001–0.01 M_\odot yr\(^{-1}\), Kochanek 2011). In IRAS 13349, the high-opacity component (characterized by the high optical extinction suffered by the direct light), and the dust appear to be co-located, suggesting perhaps also dust formation in the IRAS 13349 outflows, be it from the torus or disc. In addition, based on sublimation temperature arguments, our placement for the iron grains (detected in the Chandra X-ray spectra) in the rim and upper layers of the torus with the silicates (detected in Spitzer IR data) in the interior, gives a picture qualitatively similar to that arrived at by Chiang et al. (2001) for the dust in the surface layers of T Tauri and Herbig Ae discs.
6 SUMMARY

Although IRAS 13349 shows many signs of being an obscured QSO, the \textit{Spitzer} spectra show it as a typical QSO. The continuum peaks at 30 \textmu m; the silicate features at 10 and 18 \textmu m are in emission and PAH features are weak. The emission lines are dominated by highly ionized species such as [Ne\emissionline{v}] and [O\emissionline{iv}]. Furthermore, even though IRAS 13349 exhibits extreme Eigenvector-1 characteristics, HET optical spectra argue against its classification as a narrow-line Seyfert 1. The high S/N ratio and $R \sim 1300$ HET data have also allowed us to improve redshift measurements for IRAS 13349, locating it at $z = 0.10855$.

In the ultraviolet, our low-resolution STIS spectra cover the observed wavelength range from 1150–3180 \textAA. These spectra show for the first time blueshifted absorption from Ly\alpha, N\emissionline{v} and C\emissionline{iv}, with components at systemic velocities of $-950 \text{ km s}^{-1}$ and $-75 \text{ km s}^{-1}$. The lines are unresolved, and they have intrinsic widths with Doppler parameters that are $\ll 200 \text{ km s}^{-1}$. As seen before (Hines et al. 2001), the UV spectrum is heavily reddened, but at the shortest wavelengths in the UV, below an observed wavelength of 1600 \textAA, the spectrum begins to recover in flux and appears less heavily reddened.

Our HETGS spectrum of IRAS 13349 covers X-ray wavelengths from 2–38 \textAA (observed). The continuum is well described by a power law with photon index $\Gamma = 1.9$. At low energies we observe a soft X-ray excess that can be modelled as a blackbody with $kT \sim 100$ eV. IRAS 13349 is well known for the ionized absorption that is prominent in its X-ray spectrum (Brandt et al. 1996, 1997; Sako et al. 2001; Longinotti et al. 2003; Holczer et al. 2007). Our spectrum shows absorption lines attributable to at least two warm absorbers at velocities comparable to the higher velocity UV absorber. The lowest ionization WA-1 is co-located with the UV absorber.

Using simultaneous \textit{Chandra} HETGS and \textit{HST}/STIS spectra obtained in 2004 February, contemporaneous ground-based optical spectra from the HET and archival \textit{Spitzer} IRS spectra from 2005 as well as IRAS, ISO and 2MASS photometry data, we have constructed a broad-band view of the SED of IRAS 13349. If we compare the observed SED of IRAS 13349 to the median QSO SED of Elvis et al. (1994), we see that the IR and X-ray bands are a good match, but the UV and optical are severely suppressed. This suggests that these portions of the spectrum are either heavily obscured and/or only viewed in scattered light. By normalizing the peak of the infrared continuum and the absorption-corrected X-ray continuum to the Elvis et al. (1994) SED, we determine that the unreddened portion of the optical continuum represents a fraction of only 20 per cent of the intrinsic light from IRAS 13349.

If we correct the observed SED of IRAS 13349 for scattering and extinction, it peaks at a rest wavelength of $\sim 1000$ \textAA. A simple sum of thermal blackbody thermal disc spectra provides a good fit to the SED. We arrive at a black hole mass $M_{\text{BH}} \sim 10^8 M_{\odot}$ for IRAS 13349 based on theoretical fits to the UV–Xray SED and the H\beta line width, independently. Theoretical considerations comparing different ionizing SEDs reveal that including the UV (i.e. disc) as part of the ionizing continuum has strong implications for the conclusions one would draw about the thermodynamic stability of the warm absorber. Specific to IRAS 13349, we find that an Xray–UV ionizing SED leads to the conclusion for a continuous distribution of ionization states in e.g. a smooth flow (this paper) versus discrete clouds in pressure equilibrium (previous work, e.g. Holczer et al. 2007).

To explain the shape of the SED, we developed a geometrical model in which we view the nuclear regions of IRAS 13349 along an LOS that passes through the upper atmosphere of an obscuring torus. This sight line is largely transparent in X-rays since the gas is ionized, but, as previously discussed, it is completely obscured by dust that blocks a direct view of the UV/optical emission region. 20 per cent of the intrinsic-UV/optical continuum is scattered into our sight line by the far wall of an obscuring torus. An additional 2.4 per cent of the direct light, which likely dominates the UV emission, is Thomson-scattered into our LOS by another off-plane component of highly ionized gas. Our model suggests that the direct LOS is probably completely obscured by dust. In the standard unified scheme, such a configuration should produce a spectrum dominated by narrow emission lines, and the object would be classified as a Type 2 QSO. However, our model also suggests that nearly all of the UV/optical light we see is scattered from the central engine. Similar inferences have been made to explain the observed properties of other infrared-selected QSOs – 2MASS J130 005 316 3214 (Schmidt et al. 2002) and 2MAXSS J10 494 334 +58 375 501 (Schmidt et al. 2007) – and the BALQSOs Mrk 231 (Gallagher et al. 2005). In each case, the view of the central engine and the scattered light, are significantly obscured and the broad-line emission is revealed primarily in scattered light. For Mrk 231, imaging polarimetry constrained the scattering region to be very compact. For IRAS 13349, we also argue that the scattering material is fairly close to the BLR.

It is likely that viewed from a higher inclination, these compact scattering regions would also be obscured and the object would be classified as a Type 2 QSO. In that case, the BLR could be revealed by light scattered much farther from the central engine, in an ionization/scattering (bi)cone in direct analogy with other highly polarized Type 2 QSOs (e.g. Hines & Wills 1993; Hines et al. 1995, 1999; Tran et al. 2000; Zakamska et al. 2005).

Future modelling of IRAS 13349 can take our picture presented above as a starting point to calculate more detailed radiative transfer models of the scattering processes that include polarization calculations. These can provide more quantitative constraints on the viewing angles and sizes of the scattering regions in our complex view of this intriguing AGN. We note further that few grating-resolution X-ray spectra exist for quasar-luminosity objects and it is important to acquire as many as possible so that their properties can be compared reliably with those of the well-studied local Seyfert galaxies. Similarly, only a few grating-resolution spectra exist for strong Fe\emissionline{ii}, weak [O\emissionline{iii}] galaxies with soft X-ray spectra that are at the extremes of Eigenvector-1, as is IRAS 13349.

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