Effects of massive star formation on the ISM of dwarf galaxies

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Abstract

We are studying star formation effects on the properties of the ISM in low metallicity environments using mid-infrared (MIR) and far-infrared (FIR) observations of starbursting dwarf galaxies taken with the Infrared Space Observatory (ISO) and the Kuiper Airborne Observatory (KAO). Effects of the hard pervasive radiation field on the gas and dust due to the dust-poor environments are apparent in both the dust and gas components. From a 158 µm [CII] survey we find enhanced I[CII]/FIR ratios in dwarf galaxies and I[CII]/I(CO) ratios up to 10 times higher than those for normal metallicity starburst galaxies. We consider MIR observations in understanding the star formation properties of dwarf galaxies and constraints on the stellar SED. Notably, the strong MIR [NeIII]/[NeII] ratios reveal the presence of current massive stellar populations < 5 My old in NGC 1569, NGC 1140 and IIZw40. The MIR unidentified infrared bands (UIBs) are weak, if present at all, as a general characteristic in low metallicity environments, revealing the destruction of the smallest carbon particles (e.g. PAHs) over large spatial scales. This is confirmed with our dust modeling: mass fractions of PAHs are almost negligible compared to the larger silicate grains emitting in the FIR as well as the small carbon grains emitting in the MIR, which appear to be the source of the photoelectric gas heating in these galaxies, in view of the [CII] cooling.

Key words: dwarf galaxies; dust; photodissociation regions; ISO

1 Introduction

To construct a comprehensive picture of a galaxy’s history, understanding the distribution of its energy budget is a fundamental step. For this we must...
consider observations covering several characteristic wavelength regimes, thus, sampling the various components of the interstellar medium (ISM). While the UV to NIR wavelength continua give us relatively direct probes of the stellar populations, this radiation is subject to varying amounts of absorption before we view it. Some of this energy is absorbed by the gas directly in HII regions or transferred to the gas in photodissociation regions (PDRs) and reemitted as molecules, bands and atomic ionic and recombination lines, from wavelengths covering the UV to FIR and beyond. Some of the stellar energy is absorbed by the dust, revealed through extinction, and reradiated in MIR to submillimeter wavelengths as thermal emission. Therefore, models of the ISM in galaxies must consider these interdependent processes and be self-consistent. Our knowledge of the wavelength window from the MIR to the FIR has been limited by the low spatial and spectral resolution provided by IRAS, and has been rather sketchy when it comes to detailed studies of the ISM of individual galaxies. The Infrared Space Observatory (ISO) [1] has been a recent turning point in this effort, providing high spectral and spatial resolution and unprecedented sensitivity in the MIR to FIR. We are incorporating our MIR and FIR observations in a study of the energy redistribution in starburst galaxies to understand the effects of the star formation on the surrounding gas and dust. Here we report the progress to date in our study of star forming low-metallicity dwarf galaxies, which, in the absence of major dynamical complications, allow us to ‘simplify’ model assumptions and the interpretation of observations.

2 Far-infrared observations: the [CII] cooling line

As an indirect probe of the star formation activity, we have obtained KAO (Kuiper Airborne Observatory) and ISO observations of the 158 µm \(^2P_{3/2} - ^2P_{1/2}\) far infrared [CII] fine structure line emission in a sample of 15 dwarf galaxies [2] with metallicities ranging from 0.1 to 0.5 solar. As the ionization potential of carbon is 11.3 eV, less than that of HI, photons escaping the HII regions, dissociate CO, and ionize carbon in the photodissociation regions (PDRs) on the surfaces of nearby molecular clouds exposed to the stellar UV radiation. The observed [CII] intensity can be traced back to the radiation source due to the fact that the UV photons heat the dust which emits thermal radiation in the MIR to submillimeter wavelengths. Energetic electrons, ejected from the dust through the photoelectric effect, heat the gas. The gas subsequently cools via emission from molecules and atomic fine structure lines, predominantly the 158 µm [CII] and the 63 µm [OI] transitions in PDRs. There has been a long history of development of PDR models which provide tools to differentiate physical properties, such as density (n), radiation field strength (\(G_0\)) and filling-factors in galaxies (see review and references in [3]).
The ratio of $I_{\text{[CII]}}/I(\text{CO})$ is a useful measure of the PDR emission relative to the molecular core emission and is an indicator of the degree of star formation activity in galaxies. Active galaxies have a ratio of $I_{\text{[CII]}}/I(\text{CO}) \sim 6300$, which is 3 times greater than that observed in more quiescent galaxies \([4]\). Our [CII] survey shows that for dwarf galaxies, this ratio ranges from 6000 to 70,000, which is up to 10 times greater than those for normal metallicity starburst galaxies (Figure 1) \([2]\). We also observe an overall enhancement in the $I_{\text{[CII]}}/\text{FIR}$ ratios (where FIR is defined as the sum of the IRAS 60 and 100 $\mu$m bands) in these regions compared to those in normal metallicity galaxies, which was also noted in the LMC \([5]\) \([6]\) \([7]\). The ratio of $I_{\text{[CII]}}/\text{FIR}$ is a direct measure of the fraction of UV energy reemerging in the [CII] cooling line, and is usually between 0.1% and 1% for normal metallicity galaxies \([4]\), while we find up to 2% for dwarf galaxies. Observations of CO in dwarf galaxies have been very challenging and the glaring underabundance of observed CO in dwarf galaxies and relatively high FIR/CO luminosities have often been interpreted as unusually high star formation efficiency. While all these observational effects are a consequence of the lower metal abundance and decreased dust to gas ratio, we do not find an unambiguous direct correlation of the $I_{\text{[CII]}}/I(\text{CO})$ and $I_{\text{[CII]}}/\text{FIR}$ ratios in our surveys with metallicity. The reduced dust abundance in these environments allows the UV radiation to penetrate deeper, leaving a smaller CO core surrounded by a larger $\text{C}^+$-emitting region, thus enhancing the $I_{\text{[CII]}}/I(\text{CO})$ ratios \([8]\). Consequently, as the FUV flux travels further, the intensity becomes geometrically diluted, resulting in a lower beam-averaged FIR flux, accounting for the increased $I_{\text{[CII]}}/\text{FIR}$ ratios \([9]\).

Using the results of recent PDR models that consider the effects of reduced metallicity \([10]\), we can find solutions for the dwarf galaxies for clouds in our beam described by 2 different cases. One possible solution (case A) is for clouds with low $A_v$ ($\sim 3$) and equal densities ($n$) in the CO and $\text{C}^+$-emitting regions with $n$ ranging from $10^3$ to $10^{4.5}$ cm$^{-3}$ and low to moderate $G_o$ (normalized to the local interstellar radiation field intensity, $1.3 \times 10^{-4}$ erg s$^{-1}$ cm$^{-2}$ sr$^{-1}$) ranging from $10^{1.5}$ to $10^3$. Another possible solution (case B) is a higher $A_v$ ($\sim 10$) with the density of the CO-emitting region ($n_{\text{CO}}$) $>$ the density of the $\text{C}^+$-emitting region ($n_{\text{[CII]}}$) which gives higher ranges of $G_o$ ($\sim 10^{2.5}$ to $10^{3.5}$).

We can put further constraints on these solutions through stellar population modeling. Based on our modeled SED for IIZw40, for example, case A is a solution (section 4.1). Arguments for molecular cloud stability point toward case B for the LMC \([10]\). Decreasing the $A_v$ (case A) or increasing the $n_{\text{CO}}$ relative to $n_{\text{[CII]}}$ (case B) has the similar effect of reducing the CO-emitting core and increasing the $\text{C}^+$-emitting zone and increasing the CO-to-$\text{H}_2$ conversion factor \([10]\). Based on [CII] observations in IC10, for example, we speculated that up to 100 times more $\text{H}_2$ may be ‘hidden’ in a $\text{C}^+$-emitting regions compared...
Fig. 1. [CII] survey results: comparing normal metallicity regions with low-metallicity galaxies. Lines of constant I([CII])/I(CO) ratios run diagonally across the plot and range from \( \sim 2000 \) for quiescent galaxies and Galactic molecular cloud regions [4] up to \( \sim 70,000 \) for some dwarf galaxies [2]. The ratios of both axes are normalized to the local interstellar radiation field (1.3\( \times 10^{-4} \) erg s\(^{-1} \) cm\(^{-2} \) sr\(^{-1} \)) to that deduced only from CO observations and using the Galactic CO-to-H\(_2\) conversion factor [11]. The presence of H\(_2\) in the C\(^+\) emitting region is due to the self-shielding of H\(_2\) from UV photons or shielding by dust [12] [7] [10].

3 Mid-Infrared Observations

We are studying some of these galaxies in our [CII] survey with followup MIR observations. In Figure 2 we show ISOCAM [13] spectra covering 5 to 17 \( \mu m \) for 3 galaxies from our [CII] survey, II Zw40, NGC 1140 and NGC 1569 along with that of the notoriously metal-poor SBS0335-052 [14]. The spectra represent the total emission from the galaxies except in the case of the NGC 1569 spectra, which samples the region around the H\(\alpha\) peak #2 (see [15]). As often seen in starburst galaxies (e.g. [16] [17]), the MIR spectra are dominated by steeply rising continua longward of \( \sim 10 \) \( \mu m \), as evident in NGC 1569, II Zw40 and SBS0335-052 (Figure 2). Thermal emission from hot small grains with mean temperatures of the order of 100’s of K are responsible for the MIR continuum emission. The unidentified infrared bands (UIBs) at 6.2, 7.7, 8.6, 11.3 and 12.6 \( \mu m \), are proposed to be due to aromatic hydrocarbon particles.
undergoing stochastic temperature fluctuations (i.e., PAHs [18][19]; coal grains [20]) and are observed to peak on the PDR zones around the HII regions but are destroyed deep within HII regions [21][22][23]. While the UIBs are not obvious in the spectra of IIZw40 and SBS0335-052, and are only very weakly present NGC 1569, they can be distinguished in the spectrum of NGC 1140. Several ground state fine-structure nebular lines are present also in 3 of the spectra, the most prominent being 15.6 \( \mu m \) [NeIII] (energy potential \( \sim 41 \text{ eV} \)) and 10.5 \( \mu m \) [SIV] (energy potential \( \sim 35 \text{ eV} \)). Weaker, lower energy lines may also present, such as the 8.9 \( \mu m \) [ArIII] line and the [NeII] 12.8 \( \mu m \) line, which can be blended with the 12.6 \( \mu m \) UIB. All of these spectra look very different from one another and all differ significantly from those of normal metallicity starburst galaxies. Normal starburst galaxies show prominent UIBs, in contrast to AGNs, which are devoid of UIBs (e.g. [24][16][17]). When compared to spectra characteristic of PDRs and HII regions, i.e., M17 [22][21], IIZw40 is remarkably similar to that of an HII region. In contrast, NGC 1140, which has a very flat continuum, yet very strong [NeIII] line, does have a more obvious contribution from PDR regions in its spectra. The MIR spectra of N66, the most prominent HII region in the SMC, also shows a scarcity of UIBs in the vicinity of the most massive central cluster [25], as does the low metallicity source NGC 5253 [26]. In some starburst galaxies, amorphous silicate is seen in absorption centered at 9 and 18 \( \mu m \) (e.g. [24],[16],[17]). We can fit the MIR region of the IIZw40 spectrum with a blackbody of 193 K and an absorption equivalent to \( A_v \sim 4 \). We caution interpretation of the dust temperature we derive assuming a blackbody, since the dust emitting in the MIR is expected to be undergoing stochastic heating events, rather than being in thermal equilibrium with the radiation field. The amount of absorption in IIZw40 (\( A_v \sim 4 \)) has yet to be confirmed. In SBS0335-052, a very low metallicity galaxy (1/40 solar), \( A_v \sim 20 \) deduced from the absorption in the ISOCAM MIR spectra (Figure 2) [14]. The presence of a significant amount of dust in such a low metallicity galaxy is surprising, since star formation in SBS0335-052 began as recently as 100 Myr ago [27][28]. Such high extinction implies that the current star formation rate, hidden by dust, can be underestimated by at least 50% [14]

3.1 Effects of the starburst activity on the dwarf galaxy MIR spectra

As a consequence of the decreased dust abundance in dwarf galaxies, the ISM throughout the galaxies is effected globally by the hard radiation field of the massive stellar clusters. These galaxies contain evidence for Wolf-Rayet stars [29] and super star clusters have been detected in NGC 1140 [30], NGC 1569 [31] and SBS0335-052 [32]. The harsh radiation field, which more easily permeates the ISM compared to normal metallicity environments, can destroy the UIB carriers, for example, over very extensive spatial areas. The effect of
Fig. 2. ISOCAM MIR spectra of dwarf galaxies: IIZw40, NGC 1569, NGC 1140 and SBS0335-052. The horizontal lines in SBS0335-052 are broad band measurements; the dashed line is a blackbody with $A_v \sim 20$ [14]. Note the absorption attributed to amorphous silicates at $\sim 9$ and 18 $\mu$m.

The pervasive radiation field can be witnessed in NGC 1569 (Figure 3). Photodissociation occurs on global scales. Violent activity is revealed by the H$\alpha$ distribution [15] [33] and the 15.8 $\mu$m [NeIII] emission, with giant streamers suspected to originate from the energetic winds of the super star clusters A & B, (shown in the figure as white stars). The UIBs, [SIV] and [NeIII] emission seem to avoid the super star clusters, which blow out much of the gas and dust on relatively short time scales. This effect is also seen in the CO [34], HI [35] and the H$\alpha$ [15] distribution. Likewise we see the destruction of the UIBs in the beam-averaged spectrum of the entire galaxy of IIZw40 and SBS0335-052 (due to our lack of spatial resolution we do not see the details within these galaxies in the MIR).
4 Spectral Energy Distribution

We compile broad-band data from the literature for IIZw40, NGC 1569 and NGC 1140, and together with our MIR data, construct stellar spectral energy distributions (SEDs). In doing so, we fit the observed optical and NIR data with stellar evolution models of PEGASE [36], taking into account the results of photoionization modeling of the MIR line emission using CLOUDY [37]. This is an attempt to reconstruct the input stellar spectra consistent from the viewpoints of both the stellar evolution and photoionization.

4.1 Combined stellar evolution and photoionization model results

Using PEGASE with an instantaneous star formation rate, metallicity 0.2 solar and a Salpeter IMF (with upper and lower mass cut offs of .1 and 120 solar masses), we find solutions to observed broad band stellar light for various ages and ionization parameters. Diagnostic optical and NIR lines in the literature exist for all of these sources for a variety of apertures. The ISO/CAM MIR observations also provide important diagnostic lines of neon, sulphur and argon, and has been recently addressed by others, including [38] [26] [39] [40]. For example, the [NeIII]/[NeII] ratio, is a measure of $T_{eff}$, the hardness of the radiation field, and therefore traces the massive stellar population. For the dwarf galaxies, we find [NeIII]/[NeII] ratios in the range of 5 to 10 - much higher.
than those for normal metallicity galaxies (≤1) [41]. The extreme values of the [NeIII]/[NeII] ratios are due to effects of the low-metallicities of the systems: the $T_{\text{eff}}$ of the stars increases as the metallicity decreases for a specific stellar age. High ratios of [NeIII]/[NeII] and the prominent [SIV] in these spectra limit the age of the present star formation to < 5 Myr. Beyond this age, the massive stars have died and the [NeIII]/[NeII] ratio drops dramatically. The high excitation 24.9 $\mu$m [OIV] line, covered by the ISO SWS data, is observed in some dwarf galaxies [38] and has been proposed to be due to the presence of Wolf-Rayet stars [39]. For NGC 1569, NGC 1140 and IIZw40, we construct composite stellar SEDs that require a 75% to 95% mass fraction of an ‘older’ population ranging in age from about 10 Myr to 30 Myr along with 5% to 30% of a very young population, < 5 Myr. The broad band optical and NIR data alone reveal predominantly the older population in our apertures. Figure 4 shows an example of the resultant composite SED obtained for IIZw 40, and the extreme-ultraviolet (EUV) radiation which the young, massive stellar population traces. Observational evidence for the presence of Wolf-Rayet stars also indicates a very young stellar population [42].

Fig. 4. IIZw40 SED. The synthetic stellar spectra are fit for the extinction-corrected optical to NIR data from the literature for a 12” aperture using PEGASE. The 12, 25, 60 and 100 $\mu$m data are from IRAS and the 7 and 15 $\mu$m data points are integrated over 5.0 to 8.5 $\mu$m and 12.0 to 17 $\mu$m bands, respectively, using the ISOCAM spectrum (Figure 2).
5 Dust modeling

Having modeled the radiation field above, we next use the stellar spectra of IIZw40, NGC 1569 and NGC 1140 as input to a dust model to deduce the nature of the various dust components emitting in the MIR and the FIR. This is an important step since dust plays a major role in influencing the chemical and physical state of the ISM. We use the Désert et al. model [43], which calculates the IR emission from large silicate grains (BGs), very small amorphous carbon grains (VSGs), and stochastically-heated polycyclic aromatic hydrocarbons (PAHs), for various grain size distributions. This model is rather empirical in its approach and thus does not give an exact fit to the details of the observed spectrum. For example, the 8.6 µm UIB is not well-matched and no emission from bands at wavelengths longer than 11.3 µm are included. The model is currently in the process of modification using up-to-date laboratory-measured optical constants for a wide range of likely interstellar grain materials.

5.1 Dust in low-metallicity galaxies

In Figure 5.1 we show, as an example, the ISOCAM MIR spectrum and the IRAS data points for IIZw40 and NGC 1569, where we have plotted the emission from the PAH (dashed line), VSG (dotted line) and BG (dashed-dotted line) components. In these galaxies the MIR spectrum is clearly dominated by emission from VSGs with very little PAH emission. The BG component dominates the overall dust emission with mass fractions ranging from 93% to 99% for the 3 galaxies, while the PAH mass fraction is relatively insignificant - 5 orders of magnitude lower. This model gives a PAH/VSG mass ratio for NGC 1569 and IIZw 40 of 2 to 3x10^{-4} and 10 times this for NGC 1140. The Désert et al. model applied to the Galactic cirrus gives PAH/VSG mass ratio ∼ 1. Thus, even compared to the VSG population, we find an insignificant mass fraction of PAHs, reflecting the fact that the PAHs are destroyed in the hard radiation fields in these galaxies. PAHs are thought to be the primary particles responsible for the photoelectric heating process [44] and are incorporated in PDR models [10]. Our preliminary results, while not statistically robust at this stage, suggest that even in the absence of PAHs, the photoelectric effect is efficient, as both IIZw40 and NGC 1569 are relatively prominent [CII] sources from our survey. On the contrary, in NGC 1140, where PAHs are more obvious in the MIR spectra (Figure 2), we do not detect [CII]. VSGs (sizes determined from model ∼40 to 300A), which are very abundant relative to the PAHs in NGC 1569 and IIZw40, and less so in NGC 1140, may therefore, be the more efficient sources of photoelectric gas heating in these environments, rather than PAHs. More detailed studies of these galaxies will be carried out using the analytical dust model of Városi and Dwek [45], which
Fig. 5. Model results for the dust components in IIZw40 (left) and NGC 1569 (right) fitted to the ISOCAM MIR spectra and the IRAS data (boxes). Components are from the Désert et al. model [43] (see text for model explanation).

takes into account radiative transfer in a two-phase clumpy environment and considers various geometries.

6 Summary

Tracers of various components of the ISM show evidence of effects of the hard stellar radiation field in dwarf galaxies on the surrounding ISM due to the decreased dust abundance, allowing photoionization over large galactic scales to occur. From our survey of the 158 μm [CII] PDR cooling line in dwarf galaxies, we observe an increased penetration of the FUV radiation field which enhances the I[CII]/I(CO) emission in dwarf galaxies up to a factor of 10 more than in normal metallicity star burst galaxies. We also find a small enhancement in the I[CII]/FIR ratio in dwarf galaxies. Followup MIR ISOCAM spectroscopy provides details of ionic lines, UIBs and small hot small grain emission distribution in dwarf galaxies. The strong MIR [NeIII]/[NeII] ratios are signatures of the hard radiation fields and indicate the presence of young massive stellar populations in dwarf galaxies. Because of the increase in $T_{\text{eff}}$ in low metallicity environments, this ratio is enhanced at least 5 to 10 times more in dwarf galaxies than in normal metallicity galaxies. The penetrating radiation field also effects the dust components, destroying the UIBs in some dwarf galaxies on global scales, as is evident in the MIR spectra and in the dust modeling.
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References

[1] M.F. Kessler et al., A&A 315 (1996) L27.

[2] A.P. Jones, S.C. Madden, S.W.J. Colgan, N. Geis, M. Haas, P. Maloney, T. Nikola, A. Poglitsch, Extragalactic Astronomy in the Infrared, (1997) G. Mamon, T. Thuan, J.Tran Than, eds, Editions Frontières, Paris, 1997, p.101.

[3] D. Hollenbach, A.G.G.M. Tielens, Ann. Rev. Astron. Astrophys 35 (1997) 179.

[4] G.J. Stacey, N. Geis, R. Genzel, J.B. Lugten, A. Poglitsch, A. Sternberg, C.H. Townes, ApJ 373 (1991) 423.

[5] K. Mochizuki et al, ApJ 430 (1994) L37.

[6] A. Poglitsch, A. Krabbe, S.C. Madden, T. Nikola, N. Geis, L.E.B. Johansson, G.J. Stacey, A. Sternberg, ApJ 454 (1995) 293.

[7] S. Pak, D.T. Jaffe, E. F. van Dishoeck, L.E.B. Johansson, R.S. Booth, ApJ 498 (1998) 735.

[8] P. Maloney, J.H. Black APJ 325 (1988) 389.

[9] F.P. Israel, P.R. Maloney , N. Geis, F. Herrmann, S.C. Madden, A. Poglitsch, G.J. Stacey, ApJ 465 (1996) 738.

[10] M.J. Kaufman, M.G. Wolfire, D.J. Hollenbach, M.L. Luhman, ApJ (1999) in press.

[11] S.C. Madden, A. Poglitsch, N. Geis, G.J. Stacey, C.H. Townes , ApJ 483 (1997) 200.

[12] M.G. Burton, D.J. Hollenbach, A.G.G.M. Tielens, ApJ 365 (1990) 620.

[13] C.J. Cesarsky et al., A&A 315 (1996) 32.

[14] T.X. Thuan, M. Sauvage, S.C. Madden, ApJ 516 (1999) 783.

[15] W.H. Waller, ApJ 370 (1991) 144.

[16] C.C. Dudley, MNRAS 304 (1999) 549.
[17] O. Laurent, I.F. Mirabel, V. Charmandaris, P. Gallais, S.C. Madden, M. Sauvage, L. Vigroux, C. Cesarsky, A&A (2000) submitted.

[18] A. Léger, J.-L. Puget, A&A 137 (1984) L5.

[19] L.J. Allamandola, A.G.G.M. Tielens, J.R. Barker, ApJS 71 (1989) 733.

[20] R. Papoular, C. Reynaud, I. Nenner, A&A 247 (1991) 215.

[21] L. Verstraete, J.L. Puget, E. Falgarone, S. Drapatz, C.M. Wright, R. Timmermann, A&A 315 (1996) L337.

[22] D. Cesarsky, J. Lequeux, A. Abergel, M. Perault, E. Palazzi, S.C. Madden, D. Tran, A&A 315 (1996) L309.

[23] D. Tran, Ph. D. Thesis, 1998, Université Paris XI.

[24] P.F. Roche, D.K. Aitken, C.H. Smith, M.J. Ward, MNRAS 248 (1991) 606.

[25] A. Contursi, J. Lequeux, D. Cesarsky, F. Boulanger, M. Rubio, M. Hanus, M. Sauvage, D. Tran, A. Bosma, S.C. Madden, L. Vigroux, A&A 315 (2000) submitted.

[26] P.A. Crowther, S.C. Beck, A.J. Willis, P.S. Conti, P.W. Morris, R.S. Sutherland, MNRAS 304 (1999) 645.

[27] P. Papaderos, Y.I. Izotov, K.J. Fricke, T.X. Thuan, N.G. Guseva, A&A 338 (1998) 43.

[28] T.X. Thuan, Y.I. Izotov, C.B. Foltz ApJ 525 (1999) 105.

[29] D. Schaerer, T. Contini, M. Pindao, A&A 136 (1999) 35.

[30] D.A. Hunter, R.W. O’Connell, J.S. Gallagher, AJ 108 (1994) 84.

[31] R.W. O’Connell, J.S. Gallagher, D.A. Hunter, ApJ 443 (1994) 65.

[32] T.X. Thuan, Y.I. Izotov, V.A. Lipovetsky, ApJ 477 (1997) 661.

[33] C.L. Martin, ApJ 506 (1998) 222.

[34] C.L. Taylor, S. Hütttemeister, U. Klein, A. Greve, A&A 349 (1999) 424.

[35] F.P. Israel, W. van Driel, A&A 236 (1990) 323.

[36] M. Fioc, B. Rocca-Volmerange, A&A 326 (1997) 950.

[37] G.J. Ferland, Int.Rep. Dept. of Physics, U. Kentucky (1996).

[38] D. Lutz, D. Kunze, H.W.W. Spoon, M.D. Thornley, A&A 333 (1998) L75.

[39] D. Schaerer, G. Stasińska, A&A 345 (1999) L17.

[40] R. Genzel et al., A&A 335 (1998) 161.

[41] M. D. Thornley, N.M. Förster Schreiber, D. Lutz, R. Genzel, H.W.W. Spoon, D. Kunze, A. Sternberg, ApJ (2000) submitted.
[42] W.D. Vacca, P.S. Conti, ApJ 401 (1992) 543.
[43] F.-X. Désert, F. Boulanger, J.-L. Puget, A&A 237 (1990) 215.
[44] E.L.O. Bakes, A.G.G.M. Tielens, ApJ 427 (1994) 822.
[45] F. Városi, E. Dwek, ApJ 523 (1999) 265.