The Nature of Ionized Gas in Giant Elliptical Galaxies

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Abstract. I review the current understanding of the origin and nature of “warm” ionized gas in giant elliptical galaxies in the light of results of recent imaging and spectroscopic surveys. CCD imaging surveys have revealed that emission-line disks or filaments are (as a rule) associated with dust absorption, even in the X-ray brightest systems. This strongly suggests that the origin of this ionized gas is generally not through “cooling flows”; galaxy interactions are favored instead. Using data from a new spectrophotometric survey of “normal” elliptical galaxies covering the whole optical range, the extended ionized gas in giant ellipticals is found to be —without exception— of the LINER class, and most probably not powered by star formation activity. I discuss two independent pieces of evidence which suggest that the extended gas in giant ellipticals is ionized by means of a distributed source of ionization: (i) A significant correlation exists between the Hα+[N ii] luminosity and the optical luminosity within the region occupied by the ionized gas, and (ii) the ionization parameter of the gas does not change significantly with galactocentric radius. Two potential sources of ionization are evaluated: Photoionization by old hot stars (of post-AGB and/or AGB-Manqué type) and mechanical energy flux from electron conduction in hot, X-ray-emitting gas.

1. Introduction

Elliptical galaxies have long been considered to be inert stellar systems, essentially devoid of interstellar matter. However, our understanding of the nature of the multi-phase interstellar medium (ISM) in elliptical galaxies has undergone a radical change from this consensus that prevailed until the mid-1980’s. Present-day instrumental sensitivity across the electro-magnetic spectrum has revealed the presence of a complex, diverse ISM in elliptical galaxies, challenging their very definition in Hubble’s galaxy classification scheme.

Early-type galaxies are important in regard to any theory on the evolution of gas in galaxies simply because they generally don’t show any evidence for the presence of any significant amount of cool interstellar matter, compared to spiral (or irregular) galaxies. In fact, as of today, many basic physical and evolutionary relationships between the various components of the ISM in ellipticals are not yet understood, contrary to the situation in spiral galaxies (for the latter: see e.g.,

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Tinsley 1980; Knapp 1990; Brinks 1990; Ostriker 1990). A currently particularly controversial issue in this field of work is the question whether galaxy interactions or cooling flows dictate the interplay between the different components of the ISM in giant ellipticals (cf. Sparks, Macchetto & Golombek 1989; de Jong et al. 1990; Fabian, Canizares & Böhringer 1994; Goudfrooij & Trinchieri 1998). The “warm” \( T \sim 10^4 \text{ K} \) gas component (most often referred to as “ionized gas” or “optical nebulosity”) is crucial in the context of this controversy because its luminosity can dominate—at least locally—the total energy output of all (radiating) components of the ISM (see, e.g., Sparks et al. 1989; Goudfrooij 1994). It is therefore important to understand the nature of the optical nebulosity (e.g., is it physically associated with another component of the ISM?; does it trace star formation activity or is it ionized by other means?), in order to arrive at a correct description of the physics of the ISM in giant ellipticals.

The plan of this paper is as follows. I briefly review the multi-phase ISM in elliptical galaxies in Section 2. In Section 3, I discuss the physical relations of the warm gas with other components of the ISM in ellipticals, along with possible implications of the observed correlations. Section 4 discusses possible ionization mechanisms of the warm gas in the light of new results on emission-line intensity ratios from a low-resolution spectrophotometric survey of giant ellipticals.

2. The Multi-phase ISM of Elliptical Galaxies

2.1. What is the Fate of Stellar Mass Loss in Ellipticals?

The most obvious source of interstellar matter in early-type galaxies is the material injected into interstellar space by stellar winds of evolving stars. A good estimate on the steady-state mass injection rate for an old stellar population typical for elliptical galaxies is provided by the product of the birth rate of planetary nebulae with the mass difference between the main sequence turn-off mass of such old stellar populations \( M_{MSTO} \sim 1.0 \ M_\odot \) and the mean mass of white dwarfs; this estimate results in \( \dot{M} \simeq 1.5 \times 10^{-11} \ (L/L_\odot) \ M_\odot \text{ yr}^{-1} \), and should be accurate to within a factor of three (cf. Faber & Gallagher 1976). Since this mass loss mechanism must have been active since the formation epoch of giant ellipticals, it has yielded at least \( 10^{10} \ (L/10^{11} L_\odot) \ M_\odot \) at the present time, assuming a galaxy age of \( \sim 10^{10} \) yr. Note that this actually represents a strict lower limit to the accumulated material from stellar mass loss, as the mass loss rate was much higher during the era of galaxy formation when the star formation rate was very high. What is the fate of this material in ellipticals?

Cool Gas? No! With the advent of increasingly sensitive radio- and mm-wave detector technologies, several groups searched for this interstellar material in giant ellipticals through surveys of the usual tracers of cool gas (e.g., Knapp et al. 1985 (HI); Lees et al. 1991 (CO); Bregman, Hogg & Roberts 1992 (HI + CO); Wilkind, Combes & Henkel 1995 (CO)). While HI and CO detections of ellipticals are becoming more common (see contributions of Knapp and Oosterloo, this volume), it has become clear that these cold gas components are not tracing the mass lost by stars within these galaxies: The amount of cold gas

\[\text{footnote} \text{This review primarily concerns Giant ellipticals, defined here as ellipticals with } M_B < -19 \text{ (cf. Mihalas & Binney 1981).}\]
observed is orders of magnitude less than expected from accumulative mass loss, while histograms of the “normalized cold gas content” ($M_{H_1}/L_B$ and $M_{H_2}/L_B$) for ellipticals show a wide distribution without any clear peak, i.e., there seems to be no causal connection between the cold gas and the stellar content in giant ellipticals (e.g., Bregman et al. 1992). This is in strong contrast to the situation among spiral galaxies, where the amount of cold gas is proportional to the galaxy luminosity with very little scatter in the relationship (e.g., Haynes & Giovanelli 1984). These findings strongly suggest that the cold gas in ellipticals is generally of external origin (i.e., captured during galaxy interactions), and that the gas lost by stars had been blown out of these galaxies by a hot, supernova-driven wind as first proposed by Mathews & Baker (1971).

**Hot Gas!** So what is the fate of the material produced by stellar mass loss in giant ellipticals? This issue finally got substantially clarified after the first X-ray observations of giant ellipticals with the Einstein satellite were analyzed. Many giant ellipticals were found to be embedded in extended halos of X-ray emission, and the X-ray colors showed that the emission was dominated by thermal Bremsstrahlung from hot ($T \sim 10^7$ K) gas, with total gas masses of order $10^9 - 10^{11} M_\odot$ quite similar to the expected amount from accumulated mass loss (Forman, Jones & Tucker 1985). Evidence for the existence of this hot component of the ISM is currently only substantial for the most luminous ellipticals ($L_B \gtrsim 5 \times 10^{10} L_\odot$, see e.g., Kim, Fabbiano & Trinchieri 1992). Thus, only the most massive ellipticals seem to be able to retain the material lost by stellar winds and suppress the supernova-driven wind proposed by Mathews & Baker (1971) (see also Loewenstein, this volume). In this scenario, smaller ellipticals with too shallow potential wells may not see the bulk of their internally produced ISM ever again, donating it to the intracluster (or intergroup) medium.

2.2. So what about the “Warm” Ionized Gas Component?

2.2.1. Optical Surveys

“Warm” ionized gas was the first component of the ISM known to exist in a number of apparently “normal” ellipticals. The first notion of the frequency with which optical emission lines occur in ellipticals was provided by Mayall (1958) who examined the redshift catalog of Humason, Mayall & Sandage (1956) and found an [O ii] $\lambda 3727$ detection rate of 12% for E galaxies (and 48% for S0 galaxies). More recent long-slit spectroscopic surveys of early-type galaxies (Caldwell 1984; Phillips et al. 1986) pushed the detection rate up to about 50–55%. Phillips et al. observed the H$\alpha$ $\lambda 6563$ & [N ii] $\lambda\lambda 6548, 6583$ emission lines for a large sample of 203 E and S0 galaxies and found that the emission-line spectra of ellipticals come in two distinct flavors: (i) narrow line widths (FWHM $\lesssim 200$ km s$^{-1}$) and a small ($\lesssim 0.4$) $[\text{N ii}] \lambda 6583/\text{H}\alpha$ intensity ratio, reminiscent of normal galactic H II regions; these characteristics are found in low-luminosity ellipticals featuring blue galaxy colors, and (ii) relatively broad lines (FWHM $> 200$ km s$^{-1}$) and a large ($\gtrsim 1.0$) $[\text{N ii}] \lambda 6583/\text{H}\alpha$ ratio, which is typical for the so-called LINER class (Low-Ionization Nuclear Emission-line Regions, Heckman 1980); the latter characteristics are typically found in giant ellipticals.

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‡$H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$ is assumed throughout this paper.
While giving important information on the physical nature of the ionized gas, long-slit spectroscopy does not allow one to appreciate the full spatial extent of the emission-line gas. With this in mind, a number of teams have undertaken narrow-band CCD imaging surveys of elliptical galaxies by isolating the most prominent optical emission lines, Hα and the [N ii] λλ 6548, 6583 doublet. Kim (1989) observed 26 ellipticals and S0s detected by IRAS, Shields (1991) observed 46 galaxies detected at X-ray wavelengths, Trinchieri & di Serego Alighieri (1991) observed 13 X-ray-emitting ellipticals that are not at the center of clusters, Buson et al. (1993) observed 15 ellipticals already known to exhibit emission lines in their spectra, Goudfrooij et al. (1994) observed a optically complete sample of 56 ellipticals from the Revised Shapley-Ames (RSA) catalog, Singh et al. (1995) observed 7 X-ray bright ellipticals and S0s, and Macchetto et al. (1996) observed a sample of 73 ellipticals and S0s representing a broad variety of X-ray, radio, far-IR and kinematical properties. These surveys have shown that the ionized gas in ellipticals typically has an extended distribution (often out to several kpc from the center), and can have a plethora of different morphologies: smoothly following the stellar isophotes, flattened disk-like structures, or filamentary structures that do not resemble the underlying stellar isophotes whatsoever.

2.2.2. Relations of the Warm Ionized Gas with other Galaxy Properties

In the light of the results of the narrow-band imaging surveys mentioned above, I will discuss relations between the warm ionized gas component and other relevant (stellar as well as interstellar) properties of ellipticals in the following paragraphs. In case of ellipticals that were imaged in more than one of the narrow-band surveys, I have chosen to use the flux from the deepest survey available, which typically reported higher fluxes than the other one(s). This is most likely due to the fact that many ellipticals contain extended emission-line gas at low surface brightness which the shallower surveys were not able to detect. Galaxies in which no ionized gas was detected were assigned upper limits according to the 3-sigma detection limit to the emission-line surface brightness, assuming a radial extent of 1 kpc. All luminosities were derived (or converted) using $D_N - \sigma$ distances from Faber et al. (1989).

**Ionized Gas vs. Hot, X-ray-emitting Gas**  
Phillips et al. (1986) were the first to draw the attention to a possible relation between the warm ionized gas and the hot, X-ray-emitting gas in ellipticals, as was already known to be the case for central dominant cluster galaxies featuring “cooling flows” (Hu, Cowie & Wang 1985; see also Heckman et al. 1989; Fabian, Nulsen & Canizares 1991): They found emission-line gas in 12 out of 14 ellipticals which were found by Forman et al. (1985) to contain significant amounts of hot gas. This finding prompted two teams to investigate this possible relation further by means of a narrow-line imaging survey of X-ray-emitting ellipticals. However, they came up with different conclusions: Shields (1991; using a 1-m telescope) found essentially no correlation between the Hα and X-ray luminosities, whereas Trinchieri & di Serego (1991; using a 3.6-m telescope) found that galaxies with a relatively large amount of hot gas also have more powerful line emission on average, albeit with quite considerable scatter. This comparison illustrates the importance of establishing a deep emission-line surface brightness detection threshold in this line of work. After adding the results from the deep surveys of Goudfrooij et al.
Figure 1. \( H\alpha + [N\,\text{ii}] \) luminosity vs. X-ray–to–blue luminosity ratio for ellipticals detected by EINSTEIN. Filled squares are data from Macchetto et al. (1996) or Trinchieri & di Serego (1991); filled lozenges are data from Goudfrooij et al. (1994). The dashed line depicts the ratio \( L_X/L_B \) below which the X-ray emission is not primarily due to hot gas (Kim et al. 1992).

While Fig. 1 does reveal a positive trend in the sense that galaxies with larger hot gas content typically have high \( H\alpha + [N\,\text{ii}] \) luminosities as well, the scatter in the relation is significant: some galaxies with high \( L_X/L_B \) are weak \( H\alpha \) emitters, and many ellipticals that have bright, extended \( H\alpha \) emission have X-ray luminosities that are only barely above the expected contribution from stellar sources. In other words, the warm gas/hot gas connection is clearly more complex than the “standard cooling flow theory” (e.g., Fabian et al. 1991) would predict. The depth of the potential well may be reflected by the amount of hot gas retained in a reservoir of hot gas surrounding the elliptical (cf. Section 2.1), but to contain relatively large amounts of warm ionized gas at the present time, it does not seem required to contain such a deep potential well. Note that active nuclei are not powering the ellipticals with high \( H\alpha \) luminosity and low \( L_X/L_B \); their radio power is typically orders of magnitude below those of typical radio galaxies (even those of class Faranoff-Riley I), and their \( H\alpha \) flux does not correlate with radio (5 GHz) flux (Goudfrooij 1997).

Ionized Gas vs. Dust. The imaging surveys of Kim (1989) and Goudfrooij et al. (1994) revealed that warm ionized gas in ellipticals is virtually always morphologically associated with dust absorption. For instance, Goudfrooij et
Figure 2. Hα+[N II]–to–B-band luminosity ratio vs. ratio of dust mass and B-band luminosity of dusty ellipticals in the survey of Goudfrooij et al. (1994). Large symbols are ellipticals in which the Hα+[N II] emission has a large radial extent, out to beyond the radius where dust absorption could be detected. Note the clear correlation.

Goudfrooij et al. found Hα emission in 21/22 dusty ellipticals and dust in 21/31 Hα–emitting ellipticals, which is consistent with a one–to–one correlation given the selection effects (dust is undetectable in (close to) face-on configurations). This is illustrated by the fact that the mass of dust in the dust features correlates very well with the Hα+[N II] luminosity (see Fig. 2). Interestingly, this ionized gas/dust connection seems to be independent of the hot gas content of ellipticals, i.e., dust features are found in X-ray bright ellipticals just as well (see Figs. 3–4). This finding provides an important constraint for the origin of the warm ionized gas in ellipticals because if it would originate within a “cooling flow”, it should generally not be associated with dust. The lifetime of a dust grain of radius a against collisions with hot protons and α-particles (“sputtering”) in a hot gas with $T_e \sim 10^7$ K is $\tau_d = 2 \times 10^5 (n_{H}/\text{cm}^{-3}) (a/0.1 \text{ } \mu \text{m}) \text{ yr}$ (Draine & Salpeter 1979; Tielens et al. 1994), which is typically of order only $\sim 10^7$ yr for grains of radius 0.1 \text{ } \mu \text{m} (and proportionally shorter for smaller grains) in the central few kpc of X-ray bright ellipticals where the typical density is in the range 0.03 – 0.1 cm$^{-3}$ (see, e.g., Trinchieri et al. 1997). Hence, any matter that condenses out of a cooling flow in the central regions of early-type galaxies is very likely to be devoid of dust. The cooling flow gas is also unlikely to generate dust internally: While pressures in the central regions of a cooling flow ($nT \sim 10^5$–$10^6$ cm$^{-3}$ K) are high compared with typical pressures in the diffuse ISM in our Galaxy, they are still significantly lower than those of known sites of grain formation such as the atmospheres of red giant stars ($nT \sim 10^{11}$ cm$^{-3}$ K; Tielens 1990).

To explain the association of dust with warm ionized gas in X-ray bright ellipticals, Sparks et al. (1989) and de Jong et al. (1990) independently proposed an alternative to cooling flows: the so-called “evaporation flow” scenario, in which the dusty filaments arise from the interaction of a small gas-rich galaxy
Figure 3. CCD images of X-ray bright elliptical galaxies. The top panel shows a $B-I$ color-index image (grey scales) with isophotal contours of the $B$-band image superposed (thick solid lines). The bottom panel shows grey-scales of the Hα+$\text{[N ii]}$ emission (with the stellar continuum subtracted). 

**Left:** NGC 4374. **Right:** NGC 4696. Images taken from Goudfrooij et al. (1994).

with the giant elliptical, or from a tidal accretion event in which the gas and dust is stripped from a passing normal spiral. In this scenario, thermal interaction (heat conduction) between the cool accreted gas and dust and the pre-existing hot gas locally cools the hot gas (mimicking a cooling flow) while heating the cool gas and dust, thus giving rise to optical and far-infrared emission. This scenario predicts that the distribution of the X-ray emission follows that of the ionized gas closely, and that dust can be associated with the ionized gas, being gradually replenished by evaporation of cool molecular clouds brought in during the interaction (see also Goudfrooij & Trinchieri 1998). Furthermore, the metallicity of the ionized gas would be unrelated to those of the stars and the X-ray-emitting gas in this scenario.

The observed dust/ionized gas association can be regarded as strong evidence in favor of the “evaporation flow” scenario; we will be able to test the
predicted X-ray/optical association in the near future with AXAF data which will combine arcsec-scale spatial resolution with adequate energy resolution.

**Ionized Gas vs. Stellar Radiation** While there is a weak trend of the Hα+[NII] luminosities with the total B-band luminosities of the galaxies (cf. Fig. 5a), it is clear that many luminous ellipticals do not show any sign of ionized gas; furthermore, the trend is largely due to the [distance]$^2$ term in the luminosities, since the trend disappears largely in a flux-flux plot (Fig. 5b). Keep in mind, however, that the ionized gas is only present in the central parts of these galaxies, and that its distribution varies greatly from one galaxy to another. Interestingly, a plot of the Hα+[NII] luminosities vs. the B-band luminosity emitted within the region occupied by the line-emitting gas§ reveals a much more evident correlation (Fig. 5c; see also Macchetto et al. 1996), which does persist in a flux-flux plot (Fig. 5d). Taken at face value, this correlation suggests a stellar origin for the ionizing photons, in line with the recent result of Binette et al. (1994) who found that post-AGB stars within the old stellar population of ellipticals provide enough ionizing radiation to account for the observed Hα luminosities and equivalent widths. Following the prescriptions of Binette et al., predicted Hα luminosities have been calculated for the current collection of galaxies. The result is $L_{\text{H}\alpha,\text{obs}}/L_{\text{H}\alpha,\text{pred}} = 1.4 \pm 0.6$, which renders the stellar origin of ionizing photons quite plausible in general. This brings us to the final topic of this paper: the ionization properties of the gas in ellipticals.

§ defined as a circle centered on the nucleus, and with radius equal to $\sqrt{ab}$, where $a$ and $b$ are the semi-major and semi-minor axis of the area occupied by the line-emitting gas, respectively.
3. Properties of the Emission-line Spectra of Ellipticals

3.1. A new Spectrophotometric Survey

In this section I present first results on the emission-line spectra of giant ellipticals from a new, low-resolution (9–12 Å FWHM) spectrophotometric survey. The galaxy sample was the one Goudfrooij et al. (1994) used for their imaging survey (the “RSA sample”: all galaxies of type E from the RSA catalog with $B_0 < 12$ mag). An exhaustive description of the observations, data reduction and analysis is beyond the scope of this paper, and will be presented separately (MNRAS, in preparation). Here I suffice with a brief summary: The long-slit spectra have been taken with the B&C spectrograph on the ESO 1.52-m telescope (for the southern galaxies) and with the IDS spectrograph on the 2.5-m Isaac Newton Telescope of the Royal Greenwich Observatory (for the northern
galaxies). Care was taken to cover the spectral range 3600–7000 Å in each run, to include the strongest optical emission lines (from [O II] \( \lambda 3727 \) to [S II] \( \lambda 6731 \)). Exposure times were long enough to enable reliable measurements of emission-line intensity ratios not only in the nuclear region, but also for the extended gas. This is important to study the excitation mechanism of the extended gas (e.g., can it be ionized by a central AGN-like engine, or must the source of ionizing photons be extended as well?)

**The Need for Absorption-line Template Spectra**

Although now quite commonly detected by means of sensitive narrow-band imagery, the emission-line component in ellipticals is typically of low equivalent width (typically only a few Å for the strong [N II] \( \lambda 6583 \) line, and even less in the outer regions), and severely entangled with the underlying stellar population. It is therefore imperative to construct suitable stellar population templates in order to isolate the pure emission-line component. While different methods have been used in the past to build such population templates [e.g., stellar libraries (Keel 1983); integrated star cluster spectra (Bonatto et al. 1989)], I found that the absorption-line spectra of giant ellipticals typically cannot be adequately fitted using spectra of Galactic stars or star clusters. The main reasons for this problem are (i) the high metallicity of giant ellipticals, especially their nuclei, and (ii) the non-solar element ratios in ellipticals (i.e., high \( \alpha/Fe \) ratios, see e.g., González, this meeting). Hence, I chose to build templates from ellipticals that do not show any evidence (from either imaging or spectra) for either dust features or emission lines.

**Building absorption-line templates** was performed as follows. After correcting the flux-calibrated spectra for Galactic foreground extinction, velocities and velocity dispersions were measured as a function of radius for each sample elliptical, out to the outer radii of the ionized gas distribution. After converting the spectra to zero redshift, I extracted two spectra for each elliptical, namely (a) covering the central 2″, and (b) covering the region from 3″ to the outer radius of the detected Hα+[N II] emission (for the gassy ellipticals, that is; for the gas-free ellipticals, the extractions covered a similar range in radius). Line-strength measurements were then performed on all resulting spectra. Care was taken to only consider strong absorption-line indices free of any contamination by gaseous emission: I considered Ca II K (\( \lambda 3933 \)), CH (\( \lambda 4300 \), G-band), Mg \( \text{II} \) (\( \lambda 5175 \)), and Fe (\( \lambda \lambda 5270, 5335 \)). For each spectrum of a gassy elliptical (i.e., each set of measured line strengths), the final template was built by selecting all spectra of gas-free ellipticals of which the individual line strengths were the same within 2\( \sigma \), where \( \sigma \) is the uncertainty of the (individual) line strength measurement. After convolving the individual selected spectra with Gaussians to match the velocity dispersion of the gassy elliptical, the final best-fitting template was created by averaging the selected spectra, using weights proportional to the variance in the continuum (at 5500 Å) of the individual spectra.

A typical result of the template fitting procedure is shown in Fig. 6. The top spectrum represents the central 3″ of NGC 4589, a dust-lane elliptical containing ionized gas. Below that we show the best-fitting template spectrum. Note that its color is clearly bluer than that of NGC 4589; this is due to dust absorption within NGC 4589. The third spectrum shows the result of a direct subtraction of the template from the NGC 4589 spectrum, which illustrates the
Figure 6. Illustration of the absorption-line template subtraction procedure. The upper spectrum is that of the inner 3″ of NGC 4589, corrected for Galactic foreground extinction and converted to zero redshift. The second spectrum is the best-fit template spectrum, normalized to the NGC 4589 spectrum at the continuum at 4020 Å. The third spectrum is the residual, pure emission spectrum (i.e., “observed” – “template”), which is red due to extinction within NGC 4589. The fourth spectrum (bottom) is the final pure emission spectrum, derived after artificially reddening the template by $E_{B-V} = 0.10$. The spectra are shifted downwards (relative to the upper one) by arbitrary amounts along the Y-axis for ease of visualization.

3.2. Possible Ionization Mechanisms

A glance at Fig. 6 reveals that the ionized gas in the “normal” ellipticals in this sample is (virtually) always of the LINER class (see also Section 2.2.1). Several
Figure 7. Reddening-corrected line ratios for ellipticals in the “RSA sample” (see text), superposed on diagrams scanned from Veilleux & Osterbrock (1987). Their symbols were: • Seyfert 2, • LINER, ○ H II region-like object, and ☆ Narrow Emission-Line Galaxy (i.e., yet unclassified). Short-dashed curves represent power-law photoionization models from Ferland & Netzer (1983) for solar and 0.1 solar abundances (upper and lower, respectively). Ionization parameter \( U \) varies along the curves from \( 10^{-1.5} \) to \( 10^{-4} \). Solid curve divides AGNs from H II region-like objects. Open starred pentagons represent data for the nuclear 3″ of gassy ellipticals in the “RSA sample”; open squares represent data for the extended emission-line region of the same ellipticals. Left: [O III] \( \lambda 5007/\text{H} \beta \) vs. [S II] (\( \lambda 6716 + \lambda 6731/\text{H} \alpha \); Right: [O III] \( \lambda 5007/\text{H} \beta \) vs. [O I] \( \lambda 6300/\text{H} \alpha \).

Potential ionization mechanisms have been proposed to account for LINER-type spectra, including photoionization by a dilute non-stellar power-law continuum, shock heating, and turbulent mixing layers (see Filippenko 1996 for a recent review). In the case of LINERs with spatially compact emission, Ho, Filippenko & Sargent (1993) found that photoionization by a power-law continuum provides the best overall fit to the observed line ratios. However, the radial variation of the line ratios for ellipticals with extended emission (cf. Fig. 7) does not seem consistent with a nuclear source of ionization: The ionization parameter \( U \) (the ratio of the ionizing photon density to the nucleon density at the face of the gas cloud) of the gas in the outer regions seems to be consistent with that of the nuclear gas (cf. the model curves in Fig. 6). If the ionizing agent were a nuclear source, the gas density would be required to track a \( r^{-2} \) form closely (assuming the covering factor of the gas to be small), whereas X-ray measurements show that the gas density typically varies with radius as \( r^{-3/2} \) (e.g., Trinchieri et al. 1997). Taken at face value, this suggests that the gas in these ellipticals is ionized by a distributed source. In the remainder of this contribution I will discuss the applicability of two such distributed sources: Post-AGB stars and hot electrons in the X-ray-emitting gas.

Photoionization by Post-AGB Stars

As already discussed in Sect. 2, this ionization mechanism provides an obvious explanation for the observed correlation between emission-line flux and local stellar light flux, and the post-AGB stars are generally able to produce the
observed Hα+[N ii] luminosities to within a factor of 2. What about the line ratios? Fig. 8 depicts a comparison of the measured line ratios with photoionization calculations by Binette et al. (1994), for different gas abundances and ages of the underlying stellar population. Fig. 8 shows that the measured line ratios are typically quite well matched by Binette et al.’s models for $U \sim 10^{-4}$ except for the [O iii]/Hα ratio, which seems to be somewhat higher than predicted by their models. It should be noted that their model did not consider other old hot stars such as e.g., AGB-Manqué stars which likely dominate the (stellar) production of ionizing photons in giant ellipticals (see e.g., Brown et al. 1997). Also, the effect of stellar metallicity on the Lyman continuum output of post-AGB stars still has to be included. Clearly, more work on the properties of the ionizing radiation from UV-bright stars in ellipticals will help in appreciating the potential of this ionization mechanism.

**Hot Electrons in X-ray-emitting Gas**

Another ample source of heat energy is available for ellipticals containing hot gas: *Thermal conduction* by hot electrons transfers energy from the hot gas to the cooler clouds, by a flux $F_{\text{cond}}$ that saturates at a rate $\sim 5Pv_s$, the product of the pressure and the sound speed (Cowie & McKee 1977). As the flux of
photoelectric heat energy into a cloud is

\[ F_{\text{ph}} \sim \frac{P_c U (\mathcal{E}_{\text{ph}} - 13.6 \text{eV})}{2.3 k T_{\text{warm}}} \]

where \( \mathcal{E}_{\text{ph}} \) is the mean energy per ionizing photon and \( T_{\text{warm}} \sim 10^4 \text{ K} \) the temperature of the ionized gas, the ratio of the two energy fluxes is

\[ \frac{F_{\text{cond}}}{F_{\text{ph}}} \sim 7.5 \left( \frac{U}{10^{-4}} \right)^{-1} \left( \frac{v_s}{300 \text{ km s}^{-1}} \right) \left( \frac{\mathcal{E}_{\text{ph}}}{13.6 \text{eV}} - 1 \right)^{-1}. \]

Note that at the low ionization parameters observed in gassy ellipticals (\( U \sim 10^{-4} \)), thermal conduction can easily dominate photoelectric heating in a hot gas (see also Voit & Donahue 1997). However, a coupled photoionization/conduction code is needed to solve for the line emission caused by this excitation mechanism but is not yet available; in addition, further work will be necessary to determine how electrons distribute their energy throughout the cool clouds as a function of their velocity (see e.g., Voit 1991).

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**Discussion**

*G. Trinchieri:* I’d like to comment that while AXAF will of course be great for this kind of work, also ROSAT HRI data has already shown that there is a remarkable correlation between the morphology of the X-ray emission and the H\( \alpha \)+[N II] emission in a few objects. One is in fact NGC 5846, the same galaxy for which you showed that the dust correlates beautifully with the H\( \alpha \)+[N II] emission. The ROSAT PSPC data for that galaxy even suggest (the spatial resolution of PSPC data does not allow a stronger statement here) that the feature pointing to the NE in both X-ray– and H\( \alpha \) emission is cooler than the surrounding gas at the same radius. All of this seems to fit nicely into the “evaporation flow” picture.

*P. Goudfrooij:* Thanks for the comment, sounds good!

*B. Rocca-Volmerange:* The metallicity effect can vary the number of ionizing photons. Did you include this effect in your modelling of the H\( \alpha \) emission?

*P. Goudfrooij:* No, I didn’t. I considered the model of Binette et al. (1994) who used the Schönberger PAGB tracks for solar metallicity. I agree it would be very useful to re-consider Binette et al.’s model when the effects of metallicity on PAGB (and AGB-Manqué) evolution can be evaluated.

*R. Bower:* How do the gas properties depend on environment? For instance, if the gas comes from the accretion of gas-rich satellites, wouldn’t you expect this mechanism to shut off in environments with high velocity dispersion?
P. Goudfrooij: Within the sample I presented, there is indeed a hint that gassy ellipticals are preferentially found in groups or in the field. There are however exceptions, e.g., M84, M87 and NGC 4696 which are in the central regions of clusters. In those cases, I regard the more likely origin of the gas to be *stripping* from a spiral passing by too closely for its own comfort, instead of accretion of a gas-rich galaxy as a whole. This would be consistent with the fact that none of these gassy cluster ellipticals show any signs of shells.

R. Pogge: A comment about your use of the Veilleux & Osterbrock (1987) diagnostic diagrams. I would be reluctant to read too much into the various model curves they plot as regards your line data for the ellipticals. These models assume single clouds in which all of the electrons responsible for collisionally exciting the forbidden lines are photoelectrons from Hydrogen. It is pretty clear from the extended X-ray emission and Hα correlations that a lot more is going on these systems, so all bets are off. I think your point about needing to consider composite conduction & photoionization models is a more promising path to follow. There are a number of other ways to heat gas in these systems, for example turbulent mixing layers like those considered by Binette and collaborators.

P. Goudfrooij: Sure Rick, I agree with your comments. As to the simple models depicted in the Veilleux & Osterbrock diagrams: I merely mentioned them to show that the outer emission regions typically do not have a lower ionization parameter than the nuclear emission, *i.e.*, that the source of ionizing photons seems to have an extended distribution. As to models involving turbulent mixing layers, these typically give rise to the “type II” emission-line ratios seen in central cluster galaxies featuring “cooling-flows” (cf. Heckman et al. 1989), whereas “my” sample of giant ellipticals typically show “type I” line ratios.

References

Baum, S. A., Heckman, T. M., 1989, ApJ 336, 702

Binette, L., Magris, C. G., Stasińska, G., Bruzual, A. G., 1994, A&A 292, 13

Bregman, J. N., Hogg, D. E., Roberts, M. S., 1992, ApJ 387, 484

Brinks, E., 1990, in: *The Interstellar Medium in Galaxies*, eds. H. A. Thronson & J. M. Shull, Kluwer, Dordrecht, p. 39

Brown, T. M., Ferguson, H. C., Davidsen, A. F., Dorman, B., 1997, ApJ 482, 685

Buson, L. M., Sadler, E. M., Zeilinger, W. W., et al., 1993, A&A 280, 409

Caldwell, N., 1984, PASP 96, 287

Cowie L. L., McKee C. F., 1977, ApJ 211, 135

de Jong, T., Nørgaard-Nielsen, H. U., Hansen, L., Jørgensen, H. E., 1990, A&A 232, 317

Donahue, M., Voit, G. M., 1997, ApJ 486, 242

Eskridge, P. B., Fabbiano, G., Kim D.-W., 1995, ApJS 97, 141

Faber, S. M., Gallagher, J. S., 1976, ApJ 204, 365

Faber, S. M., Wegner, G., Burstein, D., et al., 1989, ApJS 69, 763

Fabian, A. C., Nulsen, P. E. J., Canizares, C. R., 1991, A&A Rev. 2, 191

Fabian, A. C., Canizares, C. R., Böhringer, H., 1994, ApJ 425, 40

Ferland, G. J., Netzer, H., 1983, ApJ 264, 105

Forman, W. R., Jones, C., Tucker, W., 1985, ApJ 293, 102

Filippenko, A. V. 1996, in: *The Physics of LINERs in View of Recent Observations*, eds. M. Eracleous et al., ASP, San Francisco, p. 17
