IONIZED GAS IN ELLIPTICAL GALAXIES

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ABSTRACT. More than half of all nearby elliptical galaxies contain modest amounts (10^3 - 10^5 $M_\odot$) of ionized gas. In bright elliptical galaxies this gas appears to lie in a rotating, kiloparsec-scale central disk, with a spectrum characteristic of non-thermal ionization. Low-luminosity ellipticals have a clumpy gas distribution and the gas in these galaxies is photoionized by young stars.

1. INTRODUCTION

Francois Schweizer has given an overview of the problem of gas and dust in elliptical galaxies. In this paper, I would like to focus in more detail on the ionized gas component. To put this into perspective, it now seems likely that a 'typical' bright elliptical galaxy has a three-phase interstellar medium, with perhaps 10^9 - 10^{10} $M_\odot$ of hot X-ray gas (Biermann and Kronberg 1983, Nulsen et al. 1984, Forman et al. 1985) and 10^6 - 10^7 $M_\odot$ of cold (HI or molecular) gas (Jura 1986, Knapp et al. 1985). In contrast, the mass of 'warm' (10^4K) gas responsible for the optical emission lines is only 10^3 - 10^5 $M_\odot$ (Phillips et al. 1986), and it therefore represents a very small fraction of the total gas content. However, this component gives us much of the information we presently have on the distribution and kinematics of gas in ellipticals, since X-ray observations are still sparse and HI detections rare.

Here, I will discuss the structure and kinematics of ionized gas in 'normal' elliptical galaxies. In doing so, I will draw heavily on the results of a recent, extensive survey of Hα/[NII] emission in early-type galaxies (Phillips et al. 1986). This work is based on high-resolution (3 Å FWHM) spectra of 203 members of a complete, magnitude-limited galaxy sample (Sadler 1984) and achieved a detection rate of about 55% to a limiting equivalent width of 0.8 Å in [NII].

2. THE EMISSION LINE SPECTRA OF ELLIPTICAL GALAXIES

The galaxies observed by Phillips et al. fall into the three categories shown in Figure 1, with their properties being roughly segregated by

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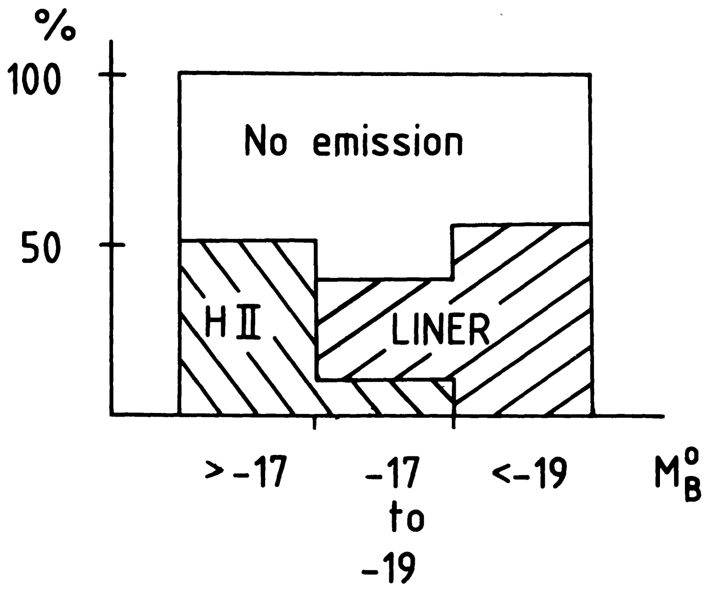

Figure 1: Fraction of E and S0 galaxies with emission spectra in the Phillips et al. survey, divided into three bins in absolute magnitude. Note that in giant ellipticals, the emission is always characteristic of a LINER (i.e. non-thermal ionization), while in the small galaxies the gas has an HII-region-like spectrum, and is ionized by young stars.

luminosity. About 40% showed no evidence for emission lines.

The emission-line spectra of bright elliptical galaxies show line ratios characteristic of LINERs (Low Ionization Nuclear Emission Regions; Heckman 1980), with Hα stronger than [NII] (see Figure 2). Such an emission spectrum can plausibly arise from either shock ionization or ionization by a central non-thermal source, but not from photoionization by young stars. NGC 1052 is the prototype of this class of objects, but all of them show similar spectra. The emission lines are weak and relatively narrow (EW 0.6 - 10 Å, FWHM 200-600 km/s), though a very weak broad-line component may also be present (Filippenko and Sargent 1985). Emission lines are more frequent, and more luminous, in brighter galaxies, suggesting that the ionized gas content increases with galaxy luminosity. The gas content does not, however, appear to be related to other galaxy properties such as color, axial ratio or stellar kinematics.

The emission lines seen in low-luminosity ellipticals resemble those in galactic HII regions, with strong, narrow lines (EW 1-20 Å, FWHM < 200 km/s) and Hα >> [NII]. Since the galaxy sample used by Phillips et al. was apparent magnitude-limited, the actual number of low-luminosity galaxies observed was small, and J.S Gallagher and I have begun a program to identify and study more members of this class.

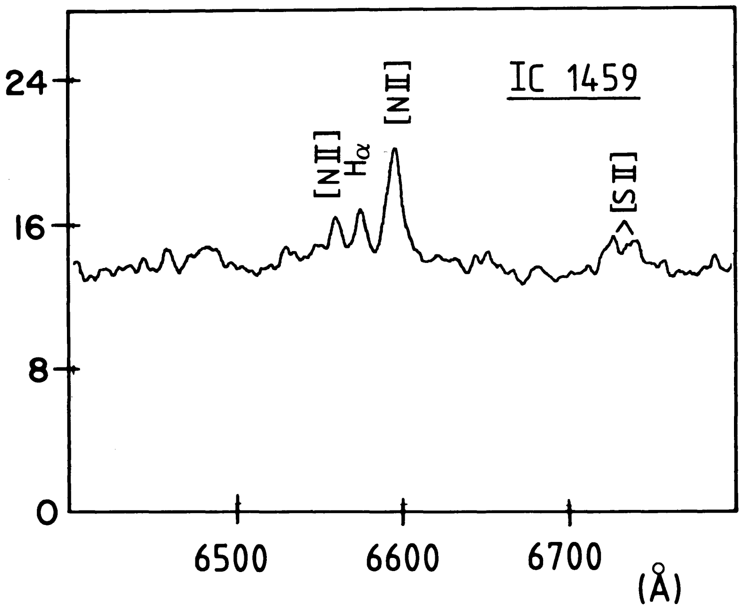

Figure 2: The spectrum of IC 1459, a typical elliptical LINER. Note that the lines are weak relative to the continuum. The vertical scale is in units of 10^{-15} ergs/cm^2/s/Å.

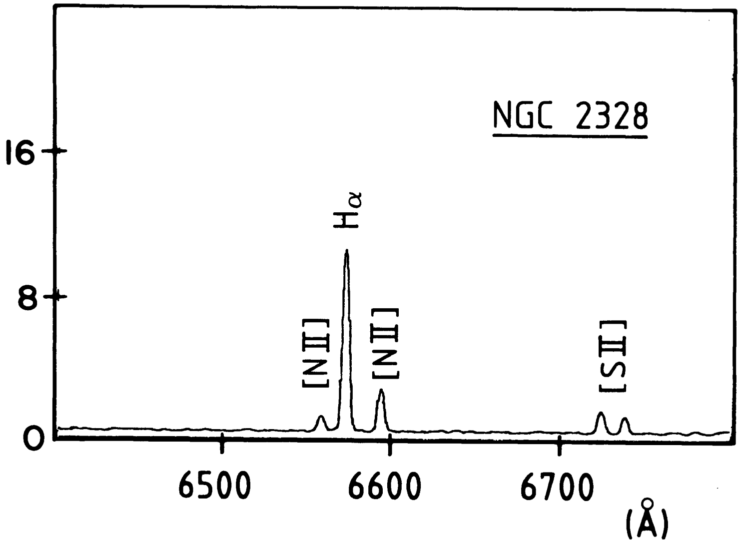

Figure 3: The spectrum of NGC 2328, a small E/S0 galaxy. Vertical scale is in units of 10^{-14} ergs/cm^2/s/Å).

Preliminary results from a survey of about 30 such galaxies confirm that somewhere between 30% and 60% of 'normal' small ellipticals contain gas which is photoionized by OB stars. Many of the galaxies which show strong emission lines are isolated, and it seems unlikely that star formation has been triggered by an external mechanism such as interaction with another galaxy. Further study of these galaxies is important in order to understand why star formation with an apparently normal IMF is proceeding in many small ellipticals, even though it is absent in giant Es.

3. STRUCTURE AND KINEMATICS OF THE LINE-EMISSION REGION

3.1 HII-region galaxies

From the Phillips et al. spectra, we can state some general properties of the HII-region galaxies. These are low-luminosity galaxies (M_B = -15 to -18 with H_o = 100 km/s/Mpc) with normal elliptical-like appearance on Schmidt plates; the gas is extended over a region 0.5 - 1 kpc in diameter and is not rotating.

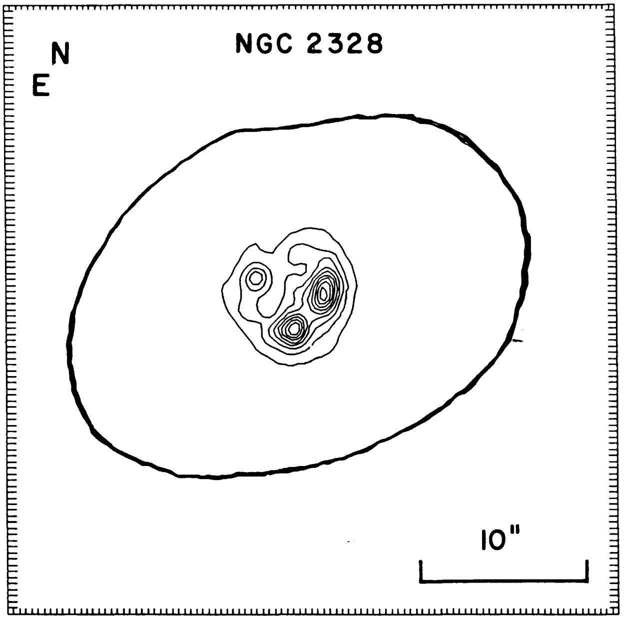

Figure 4: Distribution of emission-line gas in NGC 2328, from narrow-band CCD images obtained at the ESO 2.2m telescope. Contours indicate the strength of the Hα/[NII] emission, which is confined to the central 8-10 arcsec. The galaxy itself has a diameter of about 1.6 arcmin, and the outermost (thicker) line shows a typical continuum isophote.

Differential B-R photometry and Hα imaging of NGC 2328 show that the emission comes from a blue, ring-like structure about 0.5 kpc in diameter and centered on the nucleus of the galaxy. The ring itself is resolved into several condensations. Outside the emission region, the underlying B-V color (0.75 - 0.85) from is typical of an early-type galaxy of this luminosity (M_B = -17.0).

Although it may be unwise to speculate on the results from a single object, the observations of NGC 2328 suggest that we are seeing regions of star formation embedded in a normal (i.e. red) underlying elliptical galaxy. Most of the HII-region galaxies found by Phillips et al. are also IRAS detections, and these objects are clearly worthy of more study.

3.2 LINER galaxies

Determining the structure of the ionized gas in LINER galaxies is more difficult, since we have weak line emission against a strong galaxy continuum. About 25% of the galaxies detected by Phillips et al. had the emission region spatially resolved (at least 7 - 10 arcsec in diameter), and in these the gas lies in a region 200 pc - 2 kpc across, centered on the nucleus of the galaxy. In galaxies with extended emission, the observed gas kinematics are consistent with rapid rotation (V ~ 100-300 km/s). The total mass of ionized gas is typically 10^3 - 10^5 $M_\odot$ (see Figure 5).

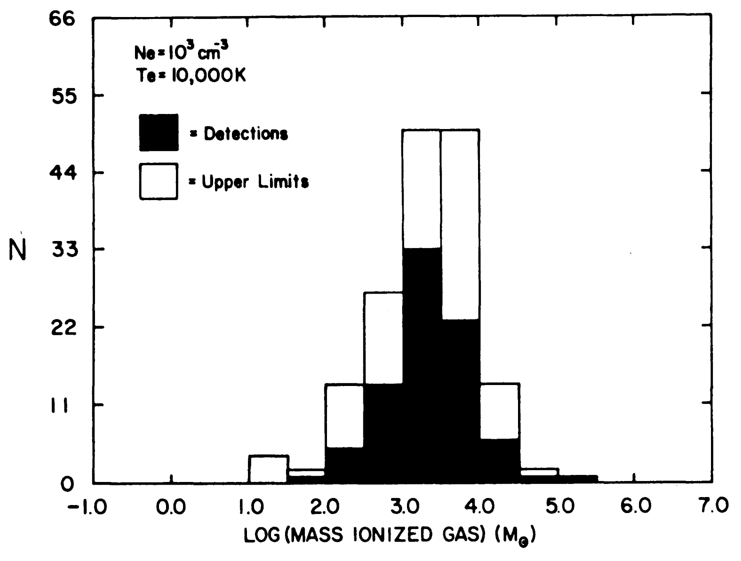

Figure 5: Distribution of ionized gas masses, from Phillips et al. (1986).

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For galaxies with strong emission lines (equivalent width 4-5 Å in [NII]), Fabry-Perot methods or CCD imaging in narrow-band filters can be used to determine the structure of the gas directly. These techniques reveal a wide range of features including filaments, warped disks and even spiral structure. F. Bertola, J. Danziger and I have recently observed several bright ellipticals in Hα/[NII] using a CCD at the ESO 2.2m telescope, and Figure 6 shows the gas morphology in two of these galaxies. NGC 4696 is the central galaxy of the Centaurus cluster, and has an X-ray cooling flow (Fabian et al. 1982). The ionized gas in this galaxy shows a complex filamentary structure, while that in NGC 5077 resembles a warped disk or bar. Demoulin-Ulrich et al. (1985) observed that the gas in NGC 5077 was extended along the minor axis of the galaxy but the higher-resolution data in Figure 6 reveal a strong twist in the gas distribution towards the center. This may be an example of gas settling into a preferred plane (Tohline et al. 1982).

The origin of the ionized gas remains uncertain. A cooling flow from the X-ray halo (Nulsen et al.1984) appears the most natural source, especially since Phillips et al. found a strong correlation between the presence of X-ray gas and emission lines. However, the rotation axes of gas and stars often differ (Bertola et al. 1984, Demoulin-Ulrich et al. 1985, Caldwell et al. 1986), and this has been used to argue that the gas has an external origin. Further work is necessary to clarify this question, and the variety of gas morphologies observed may represent gas of both internal and external origin.

4. CONCLUSION

Most elliptical galaxies have weak optical emission lines and contain modest amounts (10^3 - 10^5 $M_\odot$) of ionized gas in their central regions. Although the amount of gas present is small, it is often possible to determine both the structure and kinematics of the line-emitting region. The results show that high- and low-luminosity ellipticals form two distinct classes in terms of their emission-line properties. Low-luminosity ellipticals show spectra characteristic of HII regions, and the emission can often be resolved into individual blue clumps around the nucleus of an otherwise 'normal' (i.e. red) underlying galaxy. The emission lines are narrow, and the gas does not appear to be in ordered rotation. In contrast, the gas in bright ellipticals generally appears to lie in a rotating, kiloparsec-scale disk and the emission is LINER-like, indicating that the gas is not photoionized by young stars. There is a tendency for larger galaxies to contain more gas, but the gas content is not apparently related to other galaxy properties such as axial ratio or color. The origin of the central gas disk, and the means by which it is ionized, remain open questions.

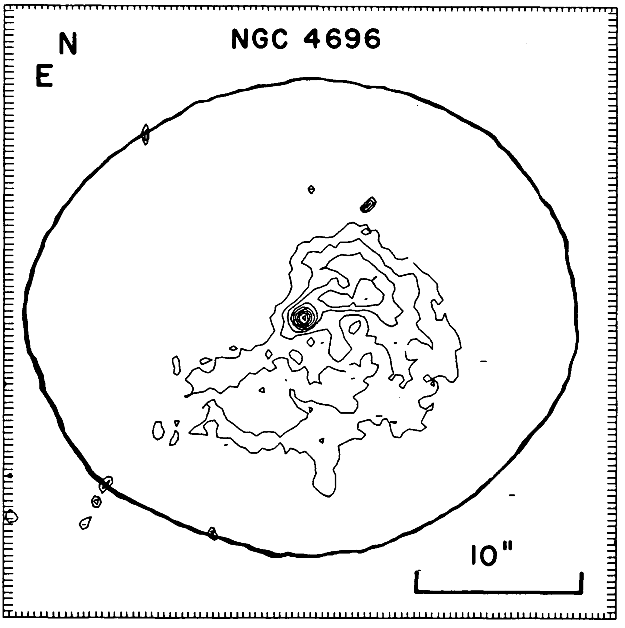
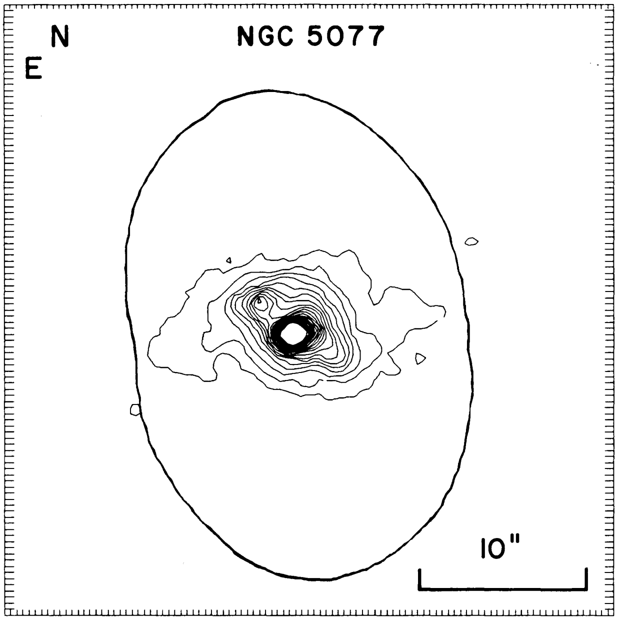


Figure 6: Distribution of emission-line gas in two bright elliptical galaxies, (a) NGC 4696 and (b) NGC 5077. As in Figure 4, contours indicate the strength of Hα/[NII] emission and the thicker line shows a continuum isophote.



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DISCUSSION

Djorgovski: It is probably not surprising that the line luminosity scales with the optical luminosity and/or X–ray luminosity. What may be much more interesting to check is whether the ratios of line to optical and X–ray to optical correlate.

Carlberg: Can you estimate the total gas mass added to the stellar core in a Hubble time, using Schweizer's estimate of 10 "accretion events" per lifetime?

Sadler: This is difficult to do just from observations of the ionized gas, since it is such a small fraction of the total gas content. We currently see $10^3 - 10^4 M_\odot$ of ionized gas within 1/2 kpc radius in a typical elliptical, while the dust suggests there may be $\sim 10^6 M_\odot$ of HI in the same region. I don't know how much of this gas comes from "accretion events" and how much from stellar mass loss; but the amount seems to be roughly similar (within an order of magnitude or so) in most of the galaxies we observed.

Richstone: Could the "Liner" Spectra be produced by photoionization by photons from the X–ray emitting gas or is some other mechanism mandated?

Sadler: Ionization by X–ray photons is certainly plausible, and perhaps even the most promising mechanism. I believe Luc Binette and Mike Dopita are currently working on models of this kind.

Porter: One problem with cooling gas inflow models with large $\dot{M}$ is that the central radio sources in the galaxies involved are rather weak, so that most of the mass cannot be reaching the central engine. Do the masses of the gas disks you observe correlate well with the radio source luminosities, and if so, can you conclude from that that the inflow is not even reaching those disks?

Sadler: There is no correlation between gas mass and radio power. We have little or no idea what happens to the gas within about 1 kpc, or how much of it reaches the nucleus.

van Gorkom: You mention a discontinuity in properties of ellipticals at the switch–over point from the $H\alpha$ regime to the Liner regime. Is this discontinuity also reflected in the radio properties?

Sadler: Yes, I think so, in the sense that radio sources are rarely seen in low–density ellipticals. We did see weak radio emission from NGC 2328; but the ratio of radio flux to $H\alpha$ flux is consistent with the radio emission coming from HII regions rather than from a central non–thermal source of the kind seen in giant ellipticals.

Schwarzschild: Are there any observable ionized disks in radio galaxies with clear axes in the center? If so, it would seem to be most instructive to see whether the innermost gas disks are aligned with the innermost radio axis.

Sadler: This is also a question which interests me very much. Unfortunately, most of the galaxies in our sample with a well–defined central gas/dust disk have compact, rather than extended radio sources. Where we do see extended radio emission in such a galaxy, as for example in NGC 4696, both the radio and emission–line components show very complex structure within the central $1 - 2$ kpc.

Ford: We are finding galaxies with Liner spectra in which there is a strong correlation between the resolved structure of nonthermal radio sources and the morphology of the ionized gas. This suggests that the gas in these galaxies may be ionized in shocks created when jets or bubbles emanating from the nucleus dissipate mechanical energy in the surrounding ISM. It also should be noted that as we see more and more symmetry in the distribution of ionized gas, it becomes increasingly difficult to account for the ionization by postulating a central, nonthermal source of ionizing photons.

Whitmore: I noticed your spectra included the SII lines. In a paper about 2 years ago, Rubin, Ford and Whitmore (1984, *Astroph. J.*, **281**, L21) found that the NII/SII ratio increases with luminosity in spiral galaxies. Do you know if this relationship also occurs in your ellipticals?

Sadler: The S/N ratio is quite poor at SII, so we have not looked in detail. However, we do note that SII increases in the low luminosity ellipticals.

Whitmore: This is the same as found in spirals. It would be interesting to determine whether the relations join together smoothly as a function of luminosity, and/or mass.

Sadler and Bertola in discussion with the audience.