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Ionized Gas in Elliptical Galaxies[1]

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Abstract. We report observations of Hα nebulosities in the X-ray bright elliptical galaxies which are members of nearby groups of galaxies or clusters. Our sample includes NGC 1399, NGC 1600, NGC 2563, NGC 3607, NGC 4203, NGC 4636, NGC 4753 and NGC 5044. Some of these galaxies have X-ray cooling flows. The results are based on CCD surface photometry carried out using the broad band filters *V* and *R*, and a narrow band filter appropriate for the red-shifted Hα + [N II] emission. We present the integrated Hα luminosities in these galaxies and examine various emission mechanisms. Photoionization by young stars is a viable mechanism. New features like dust and shells with blue colours have been discovered in some galaxies. The presence of the 10^4 K gas is associated with the presence of such features indicative of galaxy-galaxy interactions. In NGC 3607, rings or a disk of dust surrounds the ionized gas. In NGC 4753, a very complex system of dust lanes is observed. We suggest that the dust and associated gas in NGC 3607 is acquired from an interacting neighbour NGC 3608. Accretion events or mergers may be common in these galaxies.

Key words: Elliptical galaxies—surface photometry—galaxy-galaxy interactions; ionization; gas; dust.

1. Introduction

Optical spectroscopic observations have revealed that nearly 40% of the elliptical galaxies show faint emission lines (Phillips *et al.* 1986). These emission line spectra have the characteristic of LINERS (Low Ionization Nuclear Emission Regions) wherein the lines from singly ionized species are strong relative to HII regions and higher ionization lines are weak relative to AGNs. This has led to the suggestion that such spectra are typically produced by low velocity ($< 100\,\mathrm{km\,s^{-1}}$) shocks or photo-ionization by a dilute power-law continuum (Heckman 1987). In particular, Hα and [NII] emission lines are seen in the central regions of the elliptical galaxies indicating the presence of warm (10^4 K) ionized gas. The origin of the gas, its ultimate fate, and excitation mechanisms are not fully understood, however. The investigation of the above questions can be extremely interesting as it covers many topics e.g., inter-relationship of different gas phases, theory of cooling flows, frequency and relevance of mergers in

[1] Based on observations using Vainu Bappu Telescope, VBO, Kavalur.

galaxy evolution, stellar evolution, star formation etc. It is with the aim of getting an insight on these problems that we are imaging the faint emission nebulosities and studying the properties of the warm gas viz., mass, luminosity, extent, structure and shape with respect to the stellar component, association with dust and shells etc.

We have targeted the X-ray bright elliptical galaxies (Fabbiano *et al.* 1992) which are members of nearby groups of galaxies or clusters (Table 1). Diffuse X-ray emission and 'cooling flows' have been resolved in some of these galaxies (Thomas *et al.* 1986).

2. Observations

The galaxies were imaged using a GEC P8603 front-illuminated CCD at the prime focus of the 2.3 m Vainu Bappu Telescope (VBT) at Kavalur. The images were obtained through broadband V and R filters as well as narrow band filters selected appropriately for the target galaxy based on its redshift so as to cover the Hα emission. Spectrophotometric standard stars (Stone 1977) in the neighbouring regions of the sky were observed for calibrating the narrow band filter data. The standard stars in the 'dipper asterism' region of M67 (Bhat *et al.* 1992), from Landolt (1983) and Kilkenny & Menzies (1989) were observed for calibrating the V and R data. The details of the CCD camera and its standardization using the M67 star cluster have been reported by Bhat *et al.* (1990 & 1992), and Anupama *et al.* (1993). Briefly, the image scale on the CCD is 0.6 arcsec pixel^{-1} at the f/3.25 prime focus of the VBT and the field of view is 5.7×3.8 arcmin^2. The read-out noise of the CCD is ~ 10 electrons and the gain setting corresponds to ~ 4 electrons per CCD count (ADU) (Prabhu, Mayya & Anupama 1992).

3. Results

In Fig. 1, we show two representative contour maps of the surface brightness of Hα and [NII] emission from NGC 1600 and NGC 3607 derived using the R and narrow-band filter data (for details see Singh *et al.* 1993). All galaxies in our sample, except NGC 2563, were detected to have significant line emission. The emission is concentrated in the central regions. The sizes are in the range 2.0–2.5 kpc in NGC 3607, 4203, 4636 and 4753, and 4–6 kpc in NGC 1399, 1600 and 5044. The total Hα + [NII] luminosities are given in Table 1. The ratio of these luminosities to their total X-ray luminosities ranges from $\sim 2 \times 10^{-2}$ to ~ 1. X-rays may be absorbed considerably in the dust of NGC 4753, thus leading to very low observed L_x. From the V and R data we detect many *new features* like *rings and lanes reddened due to dust* in NGC 3607 and 5044, and residual *shells which are distinctly blue* in NGC 4203 and 4636 (Table 1).

4. Discussion

We have examined various emission mechanisms, such as recombination in cooling flows, heating of neutral gas associated with dust found in most of these galaxies, and ionization due to stars. Ionization in cooling flow fails to account for the observed emission nebulosities unless the recombination rate is increased by 10^2 to 10^3 times. Heat conduction, though adequate in some galaxies with small ratio of $L_{H\alpha+[NII]}$ to L_x

Table 1.

Galaxy name NGC	Type (RC3)[6]	Blue magnitude (RC3)[6]	Distance[1] (Mpc)	Log $L^2_{H\alpha+[NII]}$ (ergs s^{-1})	Log L^1_x (ergs s^{-1})	Other information[3,4,5] (Dust & shell features[2])
1399	E1	10.55	27.2	40.98	42.31	Fornax Cluster, CF, shell.
1600	E3	11.93	90.3	40.36	41.95	Group, CF, shells.
2563	SO	13.24	96.1	—	42.12	Cancer cluster, CF, shells.
3607	SO	10.82	32.0	40.63	40.88	HG56, dust rings.
4203	SAB0	11.80	15.6	40.82	40.96	GH94, Blue shell.
4636	E0	10.43	27.3	40.20	41.65	HG41, CF, Blue shell.
4753	I0	10.85	24.3	40.55	40.08	HG41, Dust lanes.
5044	E0	11.72	62.5	41.66	43.17	HG39, CF, Dust lane.

[1] Distances and L_x are from Fabbiano *et al.* (1992).
[2] Present work.
[3] HG: Group of galaxies from the Catalog by Huchra & Geller (1982).
[4] GH: Group of galaxies from the Catalog by Geller & Huchra (1983). (Also see Vennik (1986) for the N 3607 group).
[5] CF: Cooling Flow galaxies (Thomas *et al.* 1986).
[6] RC3: de Vaucouleurs *et al.* (1993).

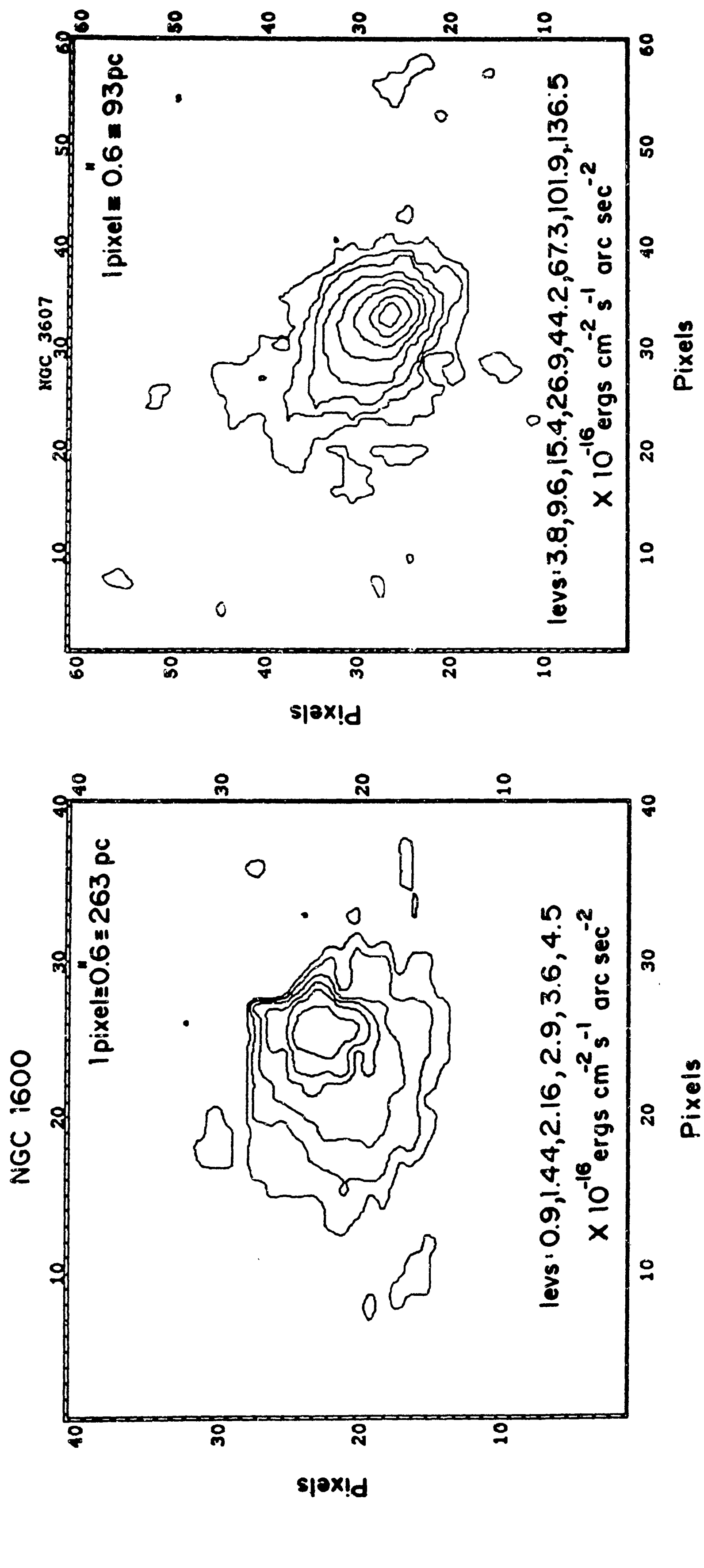

Figure 1. Surface brightness maps of Hα + [NII] emission in NGC 1600 and NGC 3607. Contour levels are indicated in the figure. East is towards the top and North is towards the right approximately.

as in NGC 4696 (Sparks, Macchetto & Golombek 1989), is found to be insufficient to match the cooling rate of the 10^4 K gas in NGC 3607 (Singh *et al.* 1993), NGC 4203 and 4753 (Singh *et al.* (in prep.)). If the ionization is due to stars, bursts of star formation and top heavy star formation are needed (Singh *et al.* 1993). In addition, the cooling timescales of the warm gas are very short and the dust cannot survive for too long in these environments. Therefore, both dust and neutral gas need to be replenished frequently. In case of NGC 3607, there is good evidence, from its rotation curve, of interaction with the gas rich neighbour NGC 3608 (Jedrzejewski & Schechter 1988) which could also be the supplier of gas and dust. The presence of shells in most galaxies (particularly those with blue colours) indicates significant ongoing merger activity and star formation. In conclusion, it appears that accretion and merger effects are common and are also the cause of enhanced star formation and ionization in these galaxies.

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References

Anupama, G. C., Kembhavi, A. K., Prabhu, T. P., Singh, K. P., Bhat, P. N. 1993, *Astr. Astrophys.*, (in press).
Bhat, P. N., Kembhavi, A. K., Patnaik, K., Patnaik, A. R., Prabhu, T. P. 1990, *Indian J. Pure & Applied Phys.*, **28**, 649.
Bhat, P. N., Singh, K. P., Prabhu, T. P., Kembhavi, A. K. 1992, *J. Astrophys. Astr.*, **13**, 293
de Vaucouleurs, G., de Vaucouleurs, A., Corwin, Jr., H. G. Buta, R. J., Puturel, G., Fouque, P., 1993, *Third reference Catalogue of Bright Galaxies*, Springer-Verlag. (RC3).
Fabbiano, G., Kim D.-W., Trinchieri, G. 1992, *Astrophys. J. Suppl.*, **80**, 531.
Geller, M. J., Huchra, J. P. 1983, *Astrophys. J. Suppl.*, **52**, 61.
Heckman, T. M. 1987, *IAU Symposium 121, Observational Evidence of Activity in Galaxies*, Ed. E. Khachikian, K. Fricke & J. Melnick, (Dordrecht: Reidel), p. 421.
Huchra, J., Geller, M. 1982, *Astrophys. J.*, **257**, 423.
Jedrzejewski, R., Schechter, P. L. 1988, *Astrophys. J.*, **330**, L87.
Kilkenny, D., Menzies, J. W. 1989, *South African Astr. Obs. Circ. No.*, **13**, 25.
Landolt, A. U. 1983, *Astr. J.*, **88**, 439.
Phillips, M. M., Jenkins, C. R., Dopita, M. A., Sadler, E. M., Binette, L. 1986, *Astr. J.*, **bf 91**, 1062.
Prabhu, T. P., Mayya, Y. D., Anupama, G. C. 1992, *J. Astrophys. Astr.*, **13**, 129.
Singh, K. P., Prabhu, T. P., Kembhavi, A. K., Bhat, P. N. 1993, *Astrophys. J.*, (submitted).
Sparks, W. B., Macchetto, F., Golombek, D. 1989, *Astrophys. J.*, **345**, 153.
Stone, R. P. S. 1977, *Astrophys. J.*, **218**, 767.
Thomas, P. A., Fabian, A. C., Arnaud, K. A., Forman, W., Jones, C. 1986, *Mon. Not. R. astr. Soc.*, **222**, 655.
Vennik, J. 1986, *Astr. Nachr.*, **307**, 157.