NGC 6251 at multiple scales and wavelengths

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Abstract.

We have studied the FR I radio galaxy NGC 6251 and its environment at several wavelengths and scale lengths. On the large scale, we have probed the gravity field by measuring the velocity dispersion of the cluster members associated with NGC 6251 and relating this to the cluster’s X-ray emission. On the small scale, the gravitational information is provided by cold HI near the nucleus and the distribution of stars and gas near the centre of the galaxy. The cold HI gas which we have measured explains the absorption of the central X-ray emission and is consistent with the extinction through the recently discovered HST gas disc of NGC 6251.

1. Introduction

NGC 6251 is an $m_B = 13^{m}6$ giant E2 radio galaxy known for its remarkable radio jet, which is aligned (within a few degrees) from pc to Mpc scales. Arguments that the galaxy contains a supermassive black hole with mass $\sim 10^9 M_\odot$ (Young et al. 1979) were recently supported by HST observations of the nuclear gas and dust disc on a scale of a few $\times 100$ pc (Ferrarese & Ford 1999). NGC 6251 lies within the confines of the Zwicky cluster Zw 1609.0+8212.

2. The optical view

It is believed that the X-ray-emitting gas detected in clusters is in equilibrium within the gravitational potential of the cluster. This means that there is a strong correlation between the X-ray gas temperature and the velocity dispersion of the member galaxies. This relation has been empirically parametrised by Girardi et al. (1996) as:

$$ (\sigma_z/km\ s^{-1}) = 10^{(2.53\pm0.04)} \times (T/keV)^{(0.61\pm0.05)} $$

We observed NGC 6251 and 12 nearby Zw1609.0+8212 galaxies (2 of which have double nuclei) with the Multiple Mirror Telescope (MMT) at 10 Å resolution (Werner, Worrall, & Birkinshaw 2000). We measured redshifts for all the sources in our sample using the standard cross-correlation technique of the stellar absorption-line spectrum with a template spectrum (Tonry & Davis 1979). In half of the cases, we were able to check the redshifts by fitting gaussians to strong emission lines.
Redshifts and projected distances from NGC 6251 enable us to rule out cluster membership for 4 galaxies, leaving 9 members of a cluster with systemic velocity \( V = 7328 \pm 105 \text{ km s}^{-1} \) and line-of-sight velocity dispersion \( \sigma_z = 283(+109,-52) \text{ km s}^{-1} \). Inserting this value into equation 1 leads to an estimated X-ray temperature of \( T = 0.7(+0.6,-0.2) \text{ keV} \) for the cluster’s gaseous atmosphere.

3. The X-ray view

ROSAT PSPC observations found 90\% of the 0.1–2 keV flux from NGC 6251 to be unresolved and coincident with the radio core (Birkinshaw & Worrall 1993). The remaining \( \sim 10\% \) of the flux appeared to originate from an extended emission component, probably a gaseous atmosphere with an FWHM of \( \sim 3 \) arcmin (130 kpc; \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \)). The limited number of counts in extended emission did not allow a useful gas temperature measurement to be made, but we have now been able to estimate it using the \( \sigma_z/T \) relation (see section 2).

Birkinshaw & Worrall (1993) measured the external pressure exerted on the radio jet by the intra-cluster medium and compared it to the minimum internal jet pressures calculated by Perley, Bridle, & Willis (1984). They found that the various sections of the jet require gas temperatures of \( T \sim 2 - 5 \text{ keV} \) to confine them. Such high temperatures are ruled out by the optical data using the correlation of equation 1, so the problem of the over-pressured jet persists in NGC 6251.

Combined ASCA and ROSAT spectroscopy of the core favour a steep X-ray spectral index and a line-of-sight column density within NGC 6251 of \( \sim 10^{21} \text{ cm}^{-2} \). This is consistent with the column density of \((1.3 \pm 0.3) \times 10^{21} \text{ cm}^{-2}\) through the HST disc derived from Ferrarese & Ford’s (1999) visual extinction of \( A_V = 0.61 \pm 0.12 \text{ mag} \).

4. The radio view

We made L-band spectral-line measurements of NGC 6251 with the VLA A-array to probe for cold gas which would be seen in absorption against the radio core. For a total of 3.2 hours of on-source time, each of the 31 channels had a width of 400 kHz (83 km s\(^{-1}\)), providing a total bandwidth of 12.5 MHz (2600 km s\(^{-1}\)).

The inner 75\% (in frequency-space) of the data were averaged to form a ‘pseudo-continuum’ or ‘channel 0’ dataset, which was mapped to produce a high-dynamic-range broadband image of NGC 6251 and its well-known radio jet (Figure 1).

The line data were reduced and a spectrum of the (unresolved) core was extracted (see Figure 2). Two absorption features are seen against the synchrotron radio continuum source. One is sightly redshifted with respect to the galaxy, and could represent infalling gas fuelling the active nucleus. The blueshifted component may correspond to an outflow or a cloud of neutral hydrogen orbiting the galaxy with a strong radial component. The two features have optical depths of \( \tau_{1386} = 0.0045 \) and \( \tau_{1383} = 0.0034 \), respectively. The combined column
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Figure 1. “Pseudo-continuum” map of the jet of NGC 6251 observed with the VLA at 21cm. Contours at 0.29 mJy × (-1, 1, 2, 4, 6, 8, 10, 12, 16, 32, 64, 128, 256, 512, 1024, 2048). Peak flux is 451 mJy/beam. Scale: 30 arcsec is equivalent to 22 kpc ($H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

density of the absorbing neutral hydrogen is $4.5 \times 10^{20} \text{ cm}^{-2}$ (assuming a spin temperature $T_s = 100 \text{ K}$).

In section 3, it was pointed out that the column densities derived from X-ray and HST observations were consistent. To this united picture we can now add a third quantity – a direct observation of cold HI gas absorbed against the radio core, indicating that perhaps the same material is responsible for the three effects.

5. Conclusions

- There is a poor cluster of galaxies associated with NGC 6251; it is one of at least three distinct subclusters that may be subunits of Zw 1609.0+8212.

- The temperature of the cluster atmosphere inferred from the velocity dispersion measurement is not high enough to provide static pressure confinement of any part of the kpc-scale radio jet (at distances of 5 to 200 kpc from the core).

- The HI spectrum shows two absorption features, one redshifted and one blueshifted with respect to the galaxy, with a combined column density $N_{HI} = 4.5 \times 10^{20} \times (T_s/100 \text{ K}) \text{ cm}^{-2}$.
Figure 2. Spectrum of the core of NGC 6251. The synchrotron radio continuum source is absorbed by neutral hydrogen along the line of sight. There are two clear absorption features, detected at > 5σ, one on either side of the (optical) redshift (marked by the dotted line). The fit consists of a baseline, slope, and two gaussians, and yields $\chi^2 = 29.3$ for 22 degrees of freedom.

- The column densities to the nucleus derived from VLA, HST, and combined ROSAT and ASCA observations are all close, and there appears to be no need for extra absorption to the central X-ray or radio source, over and above that through the HST disc.

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