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Multiband Observations of Cygnus A: A Study of Pressure Balance in the Core of a Powerful Radio Galaxy

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Cygnus A is a powerful double radio source associated with a giant elliptical galaxy at the center of a poor cluster of galaxies (see figure 1). The radio source also sits within the core radius of a dense, 'cooling flow', X-ray emitting cluster gas[1]. Optical spectroscopy and narrow band imaging have revealed copious amounts of narrow line emission from the inner 20 kpc of the associated galaxy[2,3] (we assume $H_o = 75$ km sec^{-1} Mpc^{-1}). In this short communication we discuss the pressures in the three components of the ISM (*i.e.* the radio, X-ray, and line emitting fluids) within a radius of about 15 kpc of the active nucleus of the Cygnus A galaxy.

In figure 2 we show the relative distribution of the narrow line emitting gas and the stars in the Cygnus A galaxy. Notice how the northwest peak of the broad band optical double nucleus is dominated by narrow line emission, while the southeast peak is dominated by continuum radiation (see ref. 3 for a detailed discussion). Also, notice the filamentary line emitting structures extending ≈ 10 kpc from the nucleus, to the northeast (NE) and south (S). The NE filament seems to end on a stellar like feature. This may be a foreground star, or it may be emission from something within the Cygnus A galaxy (perhaps star formation in the cooling flow?).

The integrated luminosity in $H\alpha$ and [NII] from Cygnus A is $3.1\text{x}10^{42}$ ergs sec^{-1}. An aperture spectrum of the inner 4" of this galaxy[4] yields electron temperatures of 10^4 °K and densities of 300 cm^{-3} in the line emitting regions. We calculate a volume filling factor of $1.7\text{x}10^{-6}$ for the line emitting clouds, and pressures in the clouds of $8.4\text{x}10^{-10}$ dynes cm^{-2}. Spatially resolved spectra of the various line emitting structures[2] show that the density varies spatially, with a value of about 200 cm^{-3} at the NW peak, and values of 500 cm^{-3} on the S filament, and ≤ 40 cm^{-3} on the N filament (a corresponding study of the spatial variation of temperature cannot be made from existing spectra).

In figure 3 we show the relative distribution of the radio emitting fluid and the line emitting gas in the central regions of Cygnus A. A cross marks the position of the radio nucleus (which has been blanked in order to avoid obscuring the line emission). The radio nucleus sits between the two broad band optical peaks, and the radio jet can be seen extending from the nucleus to the northwest. Notice the tendency for the NE and S filaments to extend along the boundary of the radio source. This relative morphology could be a chance projection, or it may indicate an interaction between the two fluids. Minimum energy pressures in the radio lobes are about $7.7\text{x}10^{-11}$ dynes cm^{-2}, while those in the jet are $3.1\text{x}10^{-10}$ dynes cm^{-2}.

Lastly, we consider the X-ray emitting cluster gas enveloping the system. The pressure in the inner 10 kpc of the Cygnus A galaxy cannot be determined directly from existing X-ray observations. We estimate the pressure in the X-ray emitting gas by using the value at the cluster core radius (about 200 kpc[1]), and then extrapolating the

[1]The National Radio Astronomy Observatory (NRAO) is operated by Associated Universities, Inc., under contract with the National Science Foundation.

standard cooling flow model to small radii (which implies an increase in pressure by a factor of about 3 from the cluster core radius to the center of the cluster[5]). We find a pressure of 1.7×10^{-10} dynes cm^{-2} for the X-ray gas within 10 kpc of the nucleus.

Comparing the various pressures, we see that the line emitting clouds are overpressured with respect to the radio lobes by a factor of 11, with respect to the radio jet by a factor of about 3, and with respect to the X-ray emitting fluid by a factor of 5 (of course, given the observed variation in density for the line emitting clouds, we expect variations in pressure, *e.g.* the lower density on the NE filament suggests that this feature may be in equilibrium with the radio emitting fluid. A knowledge of the spatial variation in temperature is required for a more detailed comparison).

We can reconcile the pressure difference between the radio and line emitting fluids in a number of ways. First, we can assume large departures from minimum energy conditions in the radio source. Second, we can assume minimum energy holds, but that the volume filling filling factor for the synchrotron emitting fluid in the lobes is 0.015 (the filling factor for the jet would be 0.15). Third, we could assume that ram pressure of the back flowing radio emitting fluid dominates the pressure in the lobes. A rough estimate of the ram pressure can be made by assuming that the flow is driven by the high pressure heads of the radio lobes. Minimum energy pressures in the heads are a factor of 4 larger than in the bridge, which is still a factor of 3 below line cloud pressures. Lastly, we could assume that the radio lobes and line emitting gas are not interacting, and that the spatial coincidence is just a consequence of projection.

The most likely cause for the difference between the calculated pressures in the X-ray and line emitting fluids is that the cooling flow models are incorrect. We can think of a number of mechanisms which could alter the standard model. First, magnetic fields in the cluster gas[6] may alter the heating and cooling of the gas through their influence on heat conduction. Also, if the feilds are convected with the (hypothesized) flow, they may become dynamically important at small radii (within 15 kpc, depending on geometry[3]). Second, the active nucleus may heat its environs, which would also alter the standard model. Of course, we could always assume that pressure balance does not hold between the line clouds and their environs, and hence, that they are transient phenomena.

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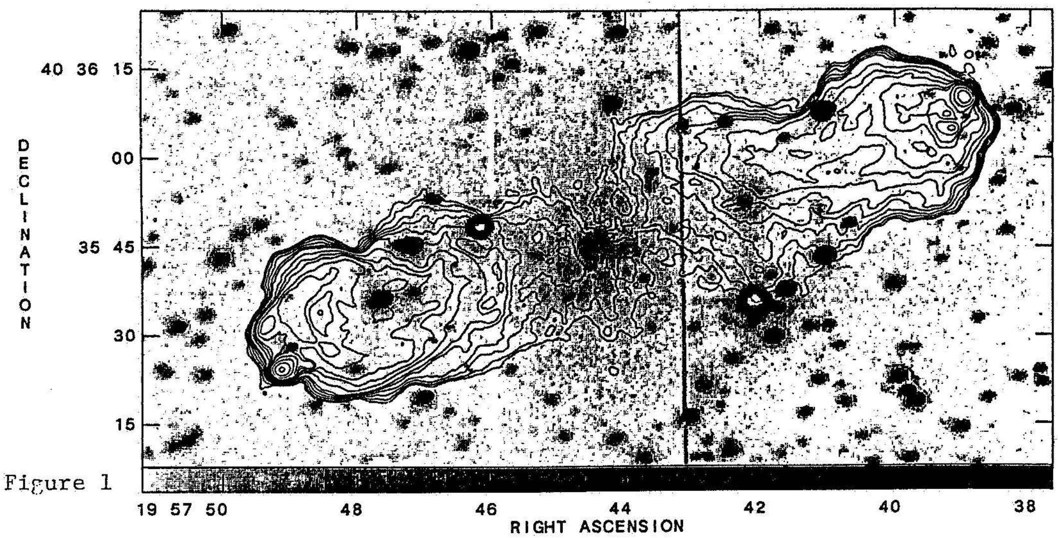

Figure 1

Figure 1: Gray Scale is an R band optical image (taken with McGraw Hill 1.3m telescope in 1.0" seeing), while contours are radio emission at 20cm (1.0" resolution VLA image). A cross marks the position of the radio core. Notice the large galaxy radius (about 40 kpc), and the way the radio lobes seem to avoid the central regions of the galaxy. Also notice the radio jet extending from the nucleus into the northwest lobe.

Figure 2: Grey scale is a broad band R image of the inner 30 kpc of the galaxy, while contoured is the optical line emission (Hα and [NII]) at the redshift of the Cygnus A galaxy (with continuum subtracted). Note how the northwest broad band peak of the double optical nucleus is mostly narrow line emission, while the southeast peak is mostly continuum. Also, note how the line emitting filament to the northeast seems to end on a compact optical feature, which may be evidence for star formation in the cooling flow, or just a foreground star.

Figure 3: Contoured is the optical line emission (Hα and [NII]) at the redshift of the Cygnus A galaxy (with continuum subtracted), while gray scale is the 20cm radio emission. Again, a cross represents the position of the radio core source (which has been blanked to better display the optical emission). Notice that the line emitting filaments extend from the nucleus both to the northeast and to the south by about 10", and seem to extend along the edge of the radio lobe.

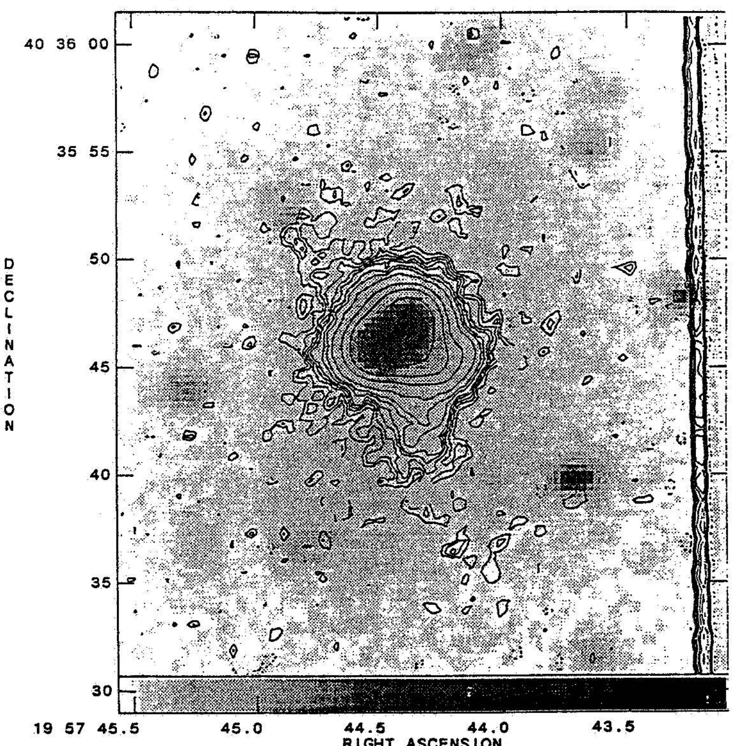

Figure 2

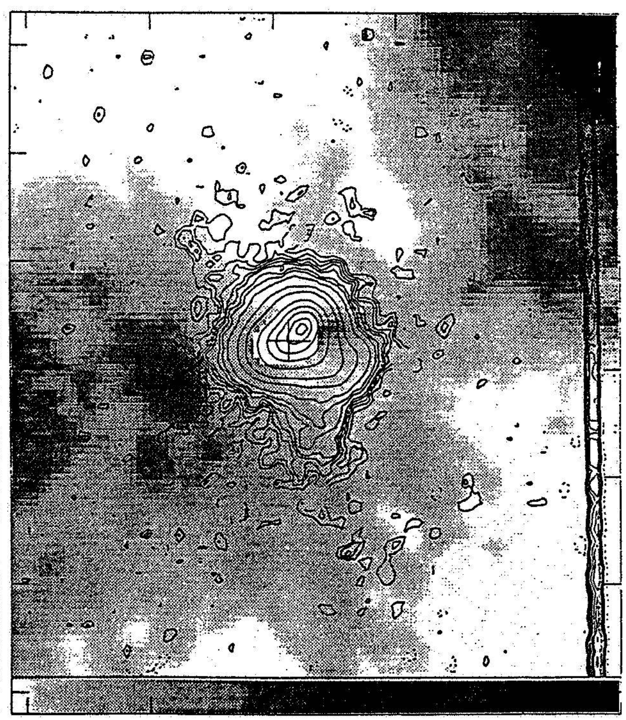
Figure 3