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Interaction of Jets with the Interstellar Medium in GPS, CSS and CSO Sources

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1. Introduction

In the past, the interaction of AGN jets with the surrounding medium has mainly been considered important only insofar as it gave us some understanding of the properties of jets. The emphasis of the work summarised here is different. In a recent paper (Bicknell, Dopita and O'Dea, 1996) we have proposed that the key optical and radio properties of Gigahertz Peak Spectrum (GPS) and Compact Steep Spectrum (CSS) sources, both treated as examples of Compact Symmetric Objects (CSOs) can be explained in terms of the interaction of a jet with a dense ISM - presumably the result of a merger. We therefore suggest that these sources represent an important evolutionary phase in Active Galactic Nuclei in which the interaction with the ISM is dominant.

The quantitative predictions of this theory are based upon the partially phemomenological model (Begelman, 1996) for dentist-drill-like evolution (Scheuer, 1982) of CSOs and has the following elements:

- The lobe bow shock is fully radiative for number densities $\gtrsim 10\,\mathrm{cm}^{-3}$ and ages $\lesssim 10^{6-7}$ yrs

- The bow shock velocity $\sim 300 - 1000\,\mathrm{km\,s}^{-1}$ and is autoinising, producing a spectrum characterized by both high and low excitation spectrum lines (see Dopita & Sutherland, 1996)

- The ionised gas surrounding the lobe has such a high column density that it free-free absorbs the radio emission at frequencies $\sim 0.1 - 10\,\mathrm{GHz}$. The characteristic low frequency power-law is the result of a spectrum of free-free opacities resulting from an inhomogeneous ISM, shock-shredding of clouds and thermal instabilities.

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- The anticorrelation between peak frequency and size, initially discovered by Fanti et al. (1990) is the result of decreasing optical depth related to the decreasing ambient density as the source increases in size.

- The rotation measure through the ionized gas is substantial, depolarizing the radio emission.

2. Correlation between Radio and Optical Emission-line Luminosities

We have calculated the $[OIII]\lambda5007$ and $H\alpha + [NII]$ line luminosities as a function of the 1.4 GHz radio power, $P_{1.4}$, using the approach of Dopita & Sutherland (1996) together with Begelman's (1996) dynamical model, giving

$$\begin{aligned} L([OIII]) &= 8.2 \times 10^{42} \left(\frac{6}{8-\delta}\right) \left(\frac{\kappa_{1.4}}{10^{-11}}\right)^{-1} \left(\frac{P_{1.4}}{10^{27}\,\mathrm{W\,Hz^{-1}}}\right) \mathrm{ergs\,s^{-1}} \\ L(H\alpha + [NII]) &= 6.2 \times 10^{42}\, \zeta^{-0.098} \left(\frac{6}{8-\delta}\right)^{0.80} n_0^{0.20} \left(\frac{\kappa_{1.4}}{10^{-11}}\right)^{-0.80} \\ &\times \left(\frac{P_{1.4}}{10^{27}\,\mathrm{W\,Hz^{-1}}}\right)^{0.80} \left(\frac{x_\mathrm{h}}{\mathrm{kpc}}\right)^{-0.20(\delta-2)} \mathrm{ergs\,s^{-1}} \end{aligned}$$

where, $\zeta \approx 2$ is the ratio of averaged pressure at the head of the lobe to average lobe pressure, δ is the index of the ambient density profile ($n_H \propto r^{-\delta}$), n_0 is the Hydrogen density at a kpc, $\kappa_{1.4}$ is the ratio of 1.4 GHz radio power to jet energy flux and x_h is the distance of the head of the lobe from the core of the galaxy. A comparison of these relations with data from various sources, is shown in Figure 1. Good agreement between theory and data is obtained for $\kappa_{1.4} \approx 10^{-10.5}$, a value which can be justified on the basis of the estimated strength of the magnetic field ($\sim 1\,\mathrm{mG}$) in GPS and CSS sources. On the other hand, the $[OIII]$ fluxes of GPS quasars are substantially reddened (Baker & Hunstead, 1996) so that correspondingly smaller values of $\kappa_{1.4}$ may be relevant.

3. The Radio Spectra and the Peak-frequency–Size Relation

The free-free optical depth is $\tau_\nu = a\nu_9^{-2.1}$ where $a = 1.1 \times 10^{-25} \int n_e^2 T_4^{-1.35}\, dl$. The contributions to a from uniform shock and precursor zones are $2.0 \times 10^{-3} V_3^{2.3} n_H$ and $1.0 \times 10^{-3} V_3^{1.5} n_H$ respectively, where $n_H\,\mathrm{cm^{-3}}$ is the pre-shock Hydrogen density and V_3 is the shock velocity in thousands of $\mathrm{km\,s^{-1}}$. A uniform medium surrounding the lobes would cut off the spectrum abruptly. However, if we assume that a is distributed as a power-law (probability density function $\propto a^p$ for constant p and $0 < a < a_0$), then, the flux density,

$$F_\nu = A \left(\frac{\nu}{\nu_0}\right)^{2.1(p+1)-\alpha} \gamma(p+1, (\nu/\nu_0)^{-2.1}) \tag{1}$$

where A is a constant, α is the high frequency spectral index, $\nu_0^{2.1} = a_0$ and $\gamma(p+1, x)$ is the incomplete gamma function. Fits of this spectrum to three

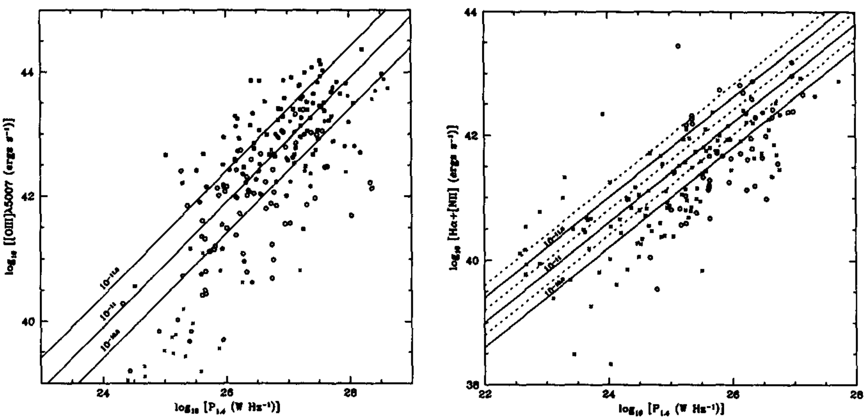

Figure 1. Left panel: Predicted $[OIII]$ luminosity – radio power relation for various values of $\log \kappa_{1.4}$ compared to the data for radio loud AGN. Filled circles, filled squares, open circles and open squares represent CSS radio galaxies, CSS quasars, radio galaxies and radio loud quasars from Gelderman and Whittle (1996); filled hexagons, open hexagons and crosses are CSS sources, FR2 and FR1 radio galaxies from Tadhunter et al. (1993) and Morganti et al. (1993). Right panel: Predicted $H\alpha + [NII]$ luminosity – radio power relation for different values of $\log \kappa_{1.4}$ overlaid on data for extragalactic radio sources. Filled circles, open circles and open stars represent CSS radio galaxies, radio galaxies and "other" radio galaxies respectively from Gelderman and Whittle (1996)

sources are shown in Figure 2. Evaluating p from low frequency spectral indices (Stanghellini et al., 1996) gives $< p > \approx -0.2$, close to a uniform distribution. (It is likely that *any* broad distribution of optical depths will lead to a spectrum of the required form.) Taking $< a >$ to be the value predicted by the uniform one-dimensional MAPPINGS models implies that the peak frequency

$$\nu_p \approx 1.1 \left(\frac{p+2}{p+1}\right)^{0.48} \left[2.0 \times 10^{-3} V_3^{2.3} + 1.0 \times 10^{-3} V_3^{1.5}\right]^{0.48} n_0^{0.48} \left(\frac{x}{\mathrm{kpc}}\right)^{-0.48\delta} \tag{2}$$

This relationship is plotted (for $\delta = 2$) and favourably compared to the Stanghellini et al (1996) data in the right hand panel of figure 2.

Another feature of this model is that the magnetionic medium surrounding the radio lobes produces substantial Faraday depolarization explaining another important characteristic of these sources. Thus, using straightforward physics, we have shown that the radio and optical properties of this class of AGN are closely related.

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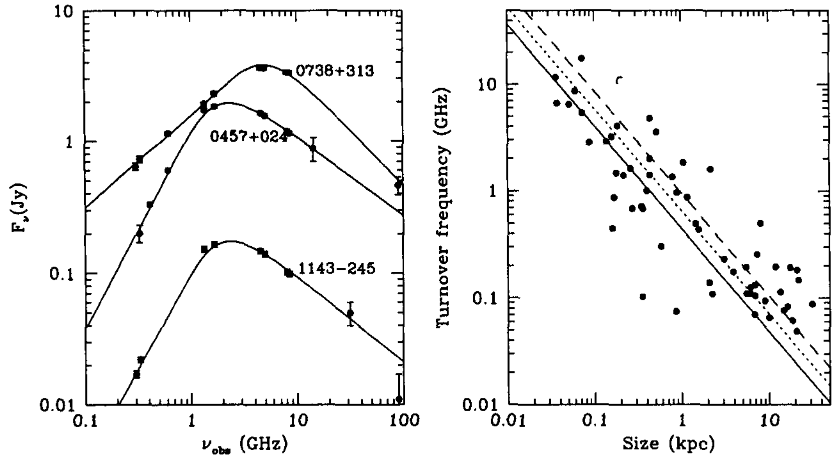

Figure 2. Left panel: Spectral fits to the data on three GPS sources. Right panel: Turnover frequency versus size relation compared to data from Stanghellini et al.(1996). Jet energy fluxes of 10^{45}, $10^{45.5}$ and 10^{46} ergs s^{-1} are represented by solid, dotted and dashed lines.

References

Baker, J. C. & Hunstead, R. W. 1996, ApJ, 452, L95

Baker, J. C., Hunstead, R. W., & Brinkmann, W. 1995, MNRAS, 277, 553

Begelman, M.C., 1996, in Cygnus A: Study of a Radio Galaxy, ed. C.L. Carilli and D.A. Harris, Canbridge University Press, Cambridge

Bicknell, G. V., Dopita, M. A., & O'Dea, C. P., 1996, ApJ, submitted

Fanti, R., Fanti, C., Schilizzi, R.T., Spencer, R. E., Rendong N., Parma, P., Van Breugel, W. J. M. and Venturi T., 1990, A&A, 231, 333

Gelderman, R. & Whittle, M., 1996, ApJ, in press

Morganti, R., Killeen, N. E. B., & Tadhunter, C. N., 1993, MNRAS, 263, 1023

Scheuer, P.A.G., 1982, in *IAU Symposium 97: Extragalactic Radio Sources*, ed. D.S. Heeschen and C.M. Wade, (Dordrecht: Reidel), 163

Stanghellini, C. O'Dea, C., Fanti, R., Baum S.A., 1996, in preparation

Sutherland, R.S. and Dopita M.A., 1993, ApJS, 88, 253

Tadhunter, C. N., Morganti, R., Aligheri, diSerego S., Fosbury, R. A. E., & Danziger, I. J. 1993, MNRAS, 263, 999

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Discussion

H. Falcke: Does it make any difference whether you assume a light or heavy jet?

G. Bicknell: A light jet will not inflate on extensive cocoon and the speed of advance of the jet through the ISM would be much higher. Thus the source dynamics would be quite different.

H. Falcke: Is there any GPS source with a low-frequency turn-over which is so steeply inverted that it requires synchronisation self-absorption?

G. Bicknell: In the Stanghellini et al. sample, the steepest low frequency spectral index is about -1.2 compared to the theoretical synchrotron self absorption value of -2.5.