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# DISCOVERY OF THE LOW-ENERGY CUTOFF IN A POWERFUL GIANT RADIO GALAXY

Katherine M. Blundell,[1] A. C. Fabian,[2] Carolin S. Crawford,[2] M. C. Erlund,[2] and Annalisa Celotti[3]
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## ABSTRACT

The lobes of radio galaxies and quasars, fed by jets and hot spots, represent a significant, and currently ill-constrained, source of energy input into the intergalactic medium (IGM). How much energy is input into the IGM depends on the *minimum* energy to which the power-law distribution of relativistic particles is accelerated in the hot spots. This has hitherto been unknown to within 3 orders of magnitude. We present direct evidence for the discovery of this low-energy cutoff in the lobe of a megaparsec-sized radio galaxy via the existence of extended X-ray emission, inverse Compton–scattered from *aged* radio plasma, and its separation by 80 kpc from regions containing *freshly accelerated* plasma from the hot spot. The low-energy cutoff of $\gamma \sim 10^4$ in the hot spot is higher than previously thought but reconciles discrepancies with magnetic field estimates that had been systematically lower than equipartition values. The inverse Compton scattering of the spent synchrotron plasma is at the expense of cosmic microwave background (CMB) photons; we comment on the importance of such giant radio galaxies as contaminants of CMB anisotropies.

*Subject headings:* galaxies: individual (6C 0905+3955) — galaxies: jets

*Online material:* color figure

## 1. INTRODUCTION

Knowledge of the energy input into the IGM from a powerful radio galaxy is necessary to understand the feedback of radio jets and lobes on their environments and hence their influence on cosmic structure formation. Estimates of this energy have been used to attempt (Wardle et al. 1998; Celotti et al. 1998; Celotti 2003) to discriminate between whether the constituents of jet plasma are electron-positron (light jets) or electron-proton (heavy jets), which has considerable implications for the jet-production mechanism at the supermassive black holes from which the jets emanate. To calculate the energy stored in the radio lobes, it is necessary to integrate over the entire energy distribution of the particles in the plasma that constitutes the lobes. The spectral shape, constrained by observations, is often a good approximation to a power law, which means that there are very few high Lorentz factor ($\gamma$) particles and many orders of magnitude more low-$\gamma$ particles. The lower limit of this energy distribution, hereafter $\gamma_{\rm min}$, was hitherto barely constrained by observations or theory (Carilli et al. 1991; Hardcastle et al. 2001) and is thus crucial for even an approximate estimate of the energies involved. A considerable range of values for $\gamma_{\rm min}$ is covered by different authors who were forced to make an arbitrary assumption (e.g., $\gamma_{\rm min} = 1$ is used by Hardcastle 2005 and also by Kaiser et al. 1997, $\gamma_{\rm min} = 10$ is used by Croston et al. 2005, $\gamma_{\rm min} = 100$ is used by Carilli et al. 1991, and $\gamma_{\rm min} = 1000$ is taken by Wardle et al. 1998). This important point is actually rather obscured by the fact that many authors state an assumed minimum frequency $\nu$ rather than a minimum $\gamma$, following Miley (1980).

## 2. COMPARISON OF X-RAY AND RADIO EMISSION

The *Chandra* X-ray satellite is revolutionizing studies of radio galaxies and quasars since it is now possible to resolve extended X-ray emission from hot spots, jets, and lobes. An extremely useful Web site documents discoveries to date.[4] While studies of jets and hot spots in these objects reveal much about speeds and magnetic fields, our focus in this Letter is on the radiation from the lobe regions (i.e., plasma that has been output from the hot spot). For *Chandra*, we proposed observations of some giant radio galaxies as part of a study to investigate the population of relativistic particles in their lobes having *lower* Lorentz factors than can be probed by radio observations of synchrotron emission. In all standard models of radio source evolution (Baldwin 1982; Kaiser et al. 1997; Blundell et al. 1999), longer (i.e., more extended) sources are older than shorter sources; as such, giant radio galaxies should be expected to have older plasma (having lower Lorentz factors than freshly accelerated plasma that has suffered less in the way of energy loss) than shorter sources.

A particularly important target among these is the powerful classical double (FR II; Fanaroff & Riley 1974) radio galaxy 6C 0905+3955, at the relatively high redshift of $z = 1.88$ (Law-Green et al. 1995). This object has a physical size projected on the plane of the sky of 945 kpc (using the assumed cosmology of $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$, and $\Omega_\Lambda = 0.73$ and its measured angular size of 111″).

The radio emission from 6C 0905+3955, shown in Figure 1 (and indeed at 408 MHz in Fig. 1*a* of Law-Green et al. 1995, which closely resembles our image at 1.4 GHz), represents the entirety of the radio emission at these frequencies: the radio lobes seen just inward of the compact hot spots, together with the core, have the same silhouette at low frequency (Law-Green et al. 1995) as at our high-frequency image shown in Figure 1. The 408 MHz MERLIN image of Law-Green et al. (1995) demonstrably does not undersample much of the smooth extended emission because the total flux density measured from the MERLIN 408 MHz image is the same as the measured total flux density of 940 mJy from the Bologna 408 MHz survey (Ficarra et al. 1985), which measures the integrated flux density. Moreover, comparison of the integrated flux density from our 1.4 GHz image (266 ± 3 mJy) with that from the NRAO VLA Sky Survey observations (260 ± 4 mJy)

[1] University of Oxford, Astrophysics, Keble Road, Oxford OX1 3RH, UK.
[2] Institute of Astronomy, Madingley Road, Cambridge CB3 0HE, UK.
[3] International School for Advanced Studies, SISSA/ISAS, via Beirut 2-4, I-34014 Trieste, Italy.

[4] See http://hea-www.harvard.edu/XJET/.

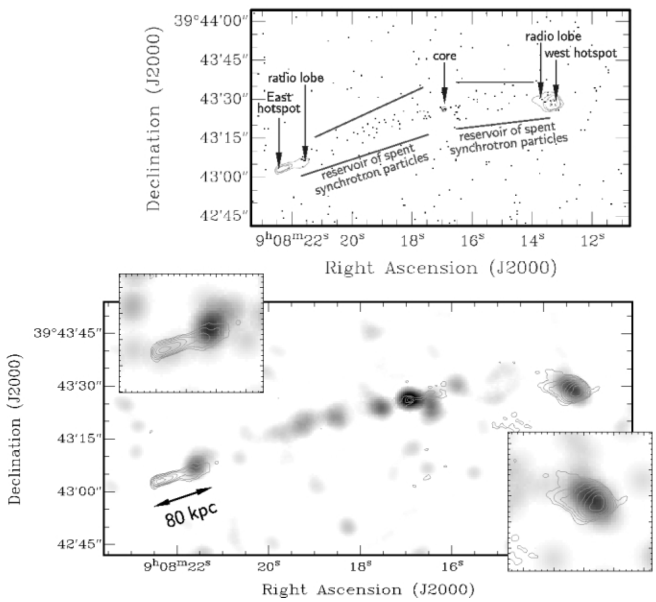


FIG. 1.—*Upper panel*: Gray scale that is unsmoothed X-ray (0.3–3 keV) emission from the giant radio galaxy 6C 0905+3955; the green contours are the radio emission at 1.4 GHz from archival observations with the A, B, and C configurations of the VLA (the lowest contour is 0.6 mJy beam$^{-1}$). Blue labels indicate the nomenclature used for the radio-emitting parts of the source, and the pairs of red lines indicate regions containing spent synchrotron lobe material having Lorentz factor particles that are too low to radiate at radio wavelengths but are sufficient to inverse Compton–scatter CMB photons to X-ray energies. *Lower panel*: Same as upper panel, but smoothed by a 4 pixel Gaussian; the contours are of the same radio emission at 1.4 GHz (the lowest contour is 0.4 mJy beam$^{-1}$). [*See the electronic edition of the Journal for a color version of this figure.*]

by Condon et al. (1998) is consistent with no radio flux density having been lost as a result of interferometric undersampling in the extended VLA configurations.

The *Chandra* X-ray satellite observed 6C 0905+3955 on 2005 March 2: the X-ray emission from this object is well detected in 19.68 ks, with about 114 counts in total (all counts quoted are background-subtracted), and is spread in a linear fashion contained within the giant radio structure (Fig. 1). The (background-subtracted) counts are divided between the lobe that contains 81 counts and the nucleus that contains 11 counts, a region with 15 counts associated with the western radio hot spot and a region containing 9 counts toward the eastern radio hot spot but actually 80 kpc from it in the direction of the nucleus. There is no indication of any host cluster or group in the relatively short exposure.

Inspection of images in different energy bands indicates that the nucleus or core is hard and that the remainder (i.e., the emission from between the hot spots but excluding the nucleus) is soft. Despite the low count rates, crude spectra are extracted and summarized in Table 1.

The unsmoothed image (the upper panel in Fig. 1) shows that the X-ray emission just to the east of the core is resolved transversely with a width of ∼25 kpc, larger than the transverse width of the radio lobe seen somewhat farther to the east, and is thus most unjet-like. The X-ray emission does not in any way resemble the fine and slender collimated jet emission that has been observed in FR I radio sources and low-redshift FR II sources (see footnote 4), and therefore strongly suggests that this X-ray emission arises from the same plasma that at earlier times would have been radio-emitting lobe material.

Comparison of the X-ray and radio structures seen in Figure 1 shows that the vast majority of the X-ray emission seems to be associated with the regions *inside* the radio lobes rather than spatially coincident with them (leaving aside the nucleus where different physics is at play). These regions are where the hot spots would have *previously* passed through, depositing then freshly accelerated plasma, on their journey outward from the central nucleus of the active galaxy. This plasma would have radiated synchrotron emission for at most a few times $10^7$ yr at observable radio wavelengths (Blundell & Rawlings 2000) and is subject to four principal kinds of energy loss (Blundell et al. 1999): (1) adiabatic expansion losses as the plasma escapes from the high-pressure hot spot into the lower pressure lobe, (2) adiabatic expansion losses as the overpressured lobe itself expands into the IGM, (3) synchrotron radiation losses, and (4) inverse Compton scattering losses off the CMB. Simple calculations show that item 1 means that the Lorentz factors of all particles will reduce by a factor of typically 10 (Scheuer & Williams 1968; Blundell et al. 1999) after exiting the compact hot spot and expanding into the lobe and item 2 means that there will be a continuous reduction in their Lorentz factors by an amount that depends on the subsequent fractional increase in volume of the lobe. (Note that items 3 and 4 make only a slight difference to the low-$\gamma$ particles since these losses depend on $\gamma^2$.) Thus, whatever is the minimum Lorentz factor ($\gamma_{\rm min}$) resulting from acceleration in the hot spot, it will give rise to a $\gamma_{\rm min}$ that is at least an order of magnitude lower in the lobes—we now establish what these values of $\gamma_{\rm min}$ are in these two locations.

TABLE 1
SPATIAL DISTRIBUTION OF X-RAY COUNTS

| Region | Total Counts (Background) | $\Gamma$ | $L_X$(2–10 keV) ($10^{44}$ ergs s$^{-1}$) |
|---|---|---|---|
| Nucleus ........... | 11 (0.14) | 2 | 1.2 |
| Lobe ............. | 81 (27.19) | $2.7^{+0.7}_{-0.7}$ | 2.1 |
| | | 2 | 2.8 |
| Westernmost ...... | 15 (2.4) | $2.5^{+0.7}_{-0.6}$ | 0.6 |
| X-rays ............ | | 2 | 0.7 |
| Easternmost | 9 (1.57) | $1.4^{+1.0}_{-0.3}$ | 0.5 |
| X-rays ............ | | 2 | 0.4 |

NOTES.—The photon numbers for detection purposes are from the 0.3–3 keV band, while the spectral fits were made over the full 0.5–7 keV band. For the easternmost X-ray–emitting region, which is some 80 kpc from the eastern radio hot spot, the probability of detecting 9 photons when 1.57 is expected is $3.9 \times 10^{-5}$, so its detection is very secure. *C*-statistics were used to calculate the X-ray photon index, $\Gamma$, and the X-ray luminosity, $L_X$, in the rest-frame 2–10 keV band. The first, third, fifth, and seventh rows in the table list the luminosity calculated for a fixed photon index of 2.

## 3. RELEVANT LORENTZ FACTORS

To suggest that the X-ray emission seen to the east of the nucleus is synchrotron emission, in a region where there is negligible radio emission even at 408 MHz (see previous section), would require an unprecedented spectrum of relativistic particles having a significant number density with Lorentz factors of $10^7$ and rather less with $10^4$, which would require an unprecedented acceleration mechanism; therefore, it is assumed that there is no particle acceleration taking place to cause this. A much more conservative explanation is the process of inverse Compton scattering of CMB (ICCMB) photons by relativistic electrons widely believed to be in the lobes of radio galaxies, which we now explore. The usual assumption is made throughout that the plasma comprising the lobe (or what used to radiate as lobe material) is not moving relativistically, and so investigation of beamed ICCMB would be inappropriate here.

Synchrotron particles with a Lorentz factor $\gamma$ will upscatter CMB photons ($\nu_{\rm CMB}$) to higher frequencies ($\nu_{\rm X}$) according to

$$\frac{\nu_{\rm X}}{\nu_{\rm CMB}} = \left(\frac{4}{3}\right)\gamma^2 - \frac{1}{3}. \qquad (1)$$

On the assumption that it is the photons from the peak of the CMB distribution that are inverse Compton–upscattered by the spent synchrotron plasma in the lobes, the Lorentz factors responsible for the emission observed at 1 and 10 keV are then $1.5 \times 10^3$ and $4.8 \times 10^3$, respectively, and so the presence of ICCMB photons mandates the existence of $\gamma \sim 10^3$ particles in the lobe region. Note that these particles will have suffered considerable adiabatic expansion losses on leaving the hot spot but preserve the shape of the spectrum. The steep power-law spectrum (if it did continue to low energies) would predict many more $\gamma \sim 10^3$ particles in the hot spot than in the lobe. However, the absence of X-ray emission, and thus ICCMB, in the east (left) hot spot mandates the absence of $\gamma \sim 10^3$ particles there; i.e., the particle spectrum in the hot spot cuts off above these low energies. If we conservatively take $\gamma_{\rm min}$ in the lobe to be $\sim 10^3$, then this requires the lower limit to the $\gamma_{\rm min}$ in the compact east hot spot to be $\sim 10^4$.

The X-rays are much more pronounced in the regions of the lobes containing spent, rather than currently radiant, synchrotron plasma. The extended X-ray emission is therefore most likely produced by nonthermal particles that no longer contribute to the observed radio emission. In fact, the X-ray emission only seems to appear where the east radio lobe has undergone significant transverse expansion (at R.A. = $09^{\rm h}08^{\rm m}21^{\rm s}.5$; see Fig. 1); still closer to the central engine, the lobe plasma has presumably undergone still further transverse expansion, so that its magnetic field strength is too low there to cause the remaining low Lorentz factor particles to radiate at radio wavelengths. However, by equation (1), the X-ray emission traces the location of old synchrotron particles, injected by the hot spot a long time ago, whose energies are now reduced down to a Lorentz factor $\gamma_{\rm min} \sim 10^3$. The lobe radio emission observed at 408 MHz (Law-Green et al. 1995) adjacent to the compact hot spots will require at least an order of magnitude higher Lorentz factor than this value of $\gamma_{\rm min}$ (assuming magnetic field strengths $\lesssim 0.1$ nT) as the particles recently accelerated in the hot spots and then released into the lobes emit synchrotron radiation in the magnetic fields there. So while electrons with such low Lorentz factors in the more aged regions of the lobes cannot produce synchrotron radiation at observable radio frequencies, they are ideally matched to upscatter CMB photons into the *Chandra* X-ray energy bands.

The radio/X-ray comparison in Figure 1 shows a separation of the outermost X-ray emission from the outermost radio emission toward the east, by ~80 kpc. This is the first direct indication of the elusive low-energy cutoff for plasma energized in hot spots, as it implies that there are no such low-energy particles in plasma recently accelerated in the hot spots. This has implications for the physical mechanism for particle acceleration in hot spots: for example, it may be that the only particles to escape from hot spots into lobes are those with gyroradii larger than the shock front, while less energetic particles with smaller gyroradii are very rapidly accelerated within the thickness of the shock (which is of course on size scales much smaller than current observations of hot spots can resolve).

The western hot spot of 6C 0905+3955 appears to be an exception to this behavior, in that there is very approximate spatial correspondence between the X-ray and radio emission (see inset to Fig. 1). It could be that on this side of the source, X-ray emission is seen much closer to the radio hot spots because expansion losses are so much greater in their vicinity (note that the transverse size of the west lobe is rather larger than that of the east lobe) and that therefore lower $\gamma$ particles are expected to be present much closer to this hot spot complex. It is also possible that different physics is responsible for this emission: for example, synchrotron self-Compton emission as found in the hot spots of Cygnus A (Wilson et al. 2001) or perhaps X-ray emission from a galaxy responsible for the putative gravitational lensing of this hot spot (Law-Green et al. 1995).

## 4. IMPLICATIONS OF A HIGH $\gamma_{\rm min}$

If the $\gamma_{\rm min}$ of the particles accelerated in the hot spots is *higher* than has previously been thought, the equipartition magnetic field strength, $B_{\rm eq}$ (calculated on the basis of the observed luminosity and the assumption that in the lobes there is equal energy stored in the magnetic fields as in the relativistic particles), will be *lower* than previously thought. The relationship between $\gamma_{\rm min}$ and $B_{\rm eq}$ is given by

$$B_{\rm eq} \propto \left(\frac{1}{\gamma_{\rm min}}\right)^{(2\alpha-1)/(3+\alpha)}, \qquad (2)$$

where $\alpha$ is the frequency spectral index of the flux density $S_\nu \propto \nu^{-\alpha}$ at frequency $\nu$. Thus, if $\gamma_{\rm min}$ of the lobes is assumed to be 10 (or 100), but is in reality $10^3$, then the inferred *B*-field is discrepantly larger than the true value by 4 (or 2). These are approximately the factors by which estimated equipartition field strengths, calculated assuming the lower values of $\gamma_{\rm min}$, are larger than independently estimated *B*-fields from cospatial inverse Compton X-ray and synchrotron radio emission (Brunetti et al. 2002; Harris & Krawczynski 2002; Kataoka et al. 2003; Croston et al. 2005). Thus, the knowledge that $\gamma_{\rm min}$ is higher than previously assumed may well reconcile these discrepant values.

If, in consequence, lobe magnetic field strengths are *lower* than previously assumed, a corollary is that a higher normalization of the particle energy spectrum is required to produce the observed luminosity (the magnetic field strength and particle number density are degenerate for a given observed synchrotron luminosity). The number density normalization $N_0$ of synchrotron particles for a power-law distribution of particles depends on $\gamma_{\rm min}$ as follows:

$$N_0 \propto \gamma_{\rm min}^{(2\alpha-1)(1+\alpha)/(3+\alpha)}, \qquad (3)$$

where $\alpha$ is the frequency spectral index measured to be $\alpha = 1.1$ in 6C 0905+3955, giving $N_0 \propto \gamma_{\rm min}^{0.6}$ in this object. The total number density $n_{\rm rel}$ is given by $n_{\rm rel} = N_0/(2\alpha\gamma_{\rm min}^{2\alpha})$.

## 5. IMPLICATIONS FOR THE RELATIVISTIC SUNYAEV-ZELDOVICH EFFECT

The dependence of the number density of particles on $\gamma_{\rm min}$ has implications for the relativistic Sunyaev-Zeldovich effect (Sunyaev & Zeldovich 1969, 1970; Birkinshaw et al. 1999) from the plasma lobes of radio galaxies. The optical depth of relativistic electrons is given (Ensslin & Kaiser 2000) by

$$\tau_{\rm rel} = \sigma_{\rm T} \int dl\, n_{\rm rel}, \qquad (4)$$

where $\sigma_{\rm T}$ is the Thomson scattering cross section, $l$ is the line-of-sight distance through the lobe (taken to be 3″, which is 25 kpc in the assumed cosmology), and $n_{\rm rel}$ is the number density of relativistic particles. The fraction of photons upscattered from the CMB via the relativistic Sunyaev-Zeldovich effect is given by $\tau_{\rm rel}$—this upscattering is assumed to be at the wavelength of the peak of the CMB photon distribution that at $z = 1.88$ is 3.7 mm, corresponding to a frequency of 82 GHz. 6C 0905+3955 is the target of future observations to search for a decrement of intensity in this frequency regime.

Taking $10^3$ for the value of $\gamma_{\rm min}$ in the lobes gives a value of $\tau_{\rm rel} \sim 10^{-10}$ for the radio-emitting regions; $\tau$ will be higher than this in the regions where X-rays are emitted. If this value of $\gamma_{\rm min}$ is typical ($\alpha > 0.5$), the radio galaxies are unlikely to be as important for CMB descrements as suggested by Ensslin & Kaiser (2000), unless the equipartition paradigm does not in general hold in these objects. Future experiments should be sensitive to CMB decrements on the angular size scales probed by giant (or relic) radio galaxies such as 6C 0905+3955 and will, in combination with future *Chandra* imaging, deepen our understanding of the physical conditions in these objects.

## 6. SUMMARY

The extended structures of the giant radio galaxy 6C 0905+3955 at X-ray and radio wavelengths have been compared, and they show that the bulk of the X-ray emission associated with noncompact components (i.e., lobe material) preferentially occurs where the synchrotron plasma is expected to be oldest. Since X-ray emission from ICCMB comes from electrons with Lorentz factors $\gamma \sim 10^3$, this strongly suggests that there is an increased presence of $\gamma \sim 10^3$ particles in the older plasma than in the more recently accelerated plasma.

If the equipartition paradigm is valid, then $\gamma_{\rm min} > 10^3$, if generally true, means that the equipartition magnetic field strengths are lower than previously assumed. The value of $\gamma_{\rm min}$ affects the optical depth of the relativistic electrons in the radio lobes; it is important to establish the generality of our discovery in order to be sure about the importance of the relativistic Sunyaev-Zeldovich effect from radio galaxy lobes imprinted in the details of the CMB.

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## REFERENCES

Baldwin, J. E. 1982, in IAU Symp. 97, Extragalactic Radio Sources, ed. D. S. Heeschen & C. M. Wade (Dordrecht: Reidel), 21
Birkinshaw, M. 1999, Phys. Rep., 310, 97
Blundell, K. M., & Rawlings, S. 2000, AJ, 119, 1111
Blundell, K. M., Rawlings, S., & Willott, C. J. 1999, AJ, 117, 677
Brunetti, G., Bondi, M., Comastri, A., & Setti, G. 2002, A&A, 381, 795
Carilli, C. L., Perley, R. A., Dreher, J. W., & Leahy, J. P. 1991, ApJ, 383, 554
Celotti, A. 2003, Ap&SS, 288, 175
Celotti, A., Kuncic, Z., Rees, M. J., & Wardle, J. F. C. 1998, MNRAS, 293, 288
Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Croston, J. H., Hardcastle, M. J., Harris, D. E., Belsole, E., Birkinshaw, M., & Worrall, D. M. 2005, ApJ, 626, 733
Ensslin, T. A., & Kaiser, C. R. 2000, A&A, 360, 417
Fanaroff, B. L., & Riley, J. M. 1974, MNRAS, 167, 31P
Ficarra, A., Grueff, G., & Tomassetti, G. 1985, A&AS, 59, 255
Hardcastle, M. J. 2005, A&A, 434, 35
Hardcastle, M. J., Birkinshaw, M., & Worrall, D. M. 2001, MNRAS, 323, L17
Harris, D. E., & Krawczynski, H. 2002, ApJ, 565, 244
Kaiser, C. R., Dennett-Thorpe, J., & Alexander, P. 1997, MNRAS, 292, 723
Kataoka, J., Leahy, J. P., Edwards, P. G., Kino, M., Takahara, F., Serino, Y., Kawai, N., & Martel, A. R. 2003, A&A, 410, 833
Law-Green, J. D. B., Eales, S. A., Leahy, J. P., Rawlings, S., & Lacy, M. 1995, MNRAS, 277, 995
Miley, G. 1980, ARA&A, 18, 165
Scheuer, P. A. G., & Williams, P. J. S. 1968, ARA&A, 6, 321
Sunyaev, R. A., & Zeldovich, Ya. B. 1969, Nature, 223, 721
———. 1970, Ap&SS, 7, 20
Wardle, J. F. C., Homan, D. C., Ojha, R., & Roberts, D. H. 1998, Nature, 395, 457
Wilson, A. S., Young, A. J., & Shopbell, P. L. 2001, ApJ, 547, 740