

High energy emission from AGN cocoons in clusters of galaxies

M. Kino^{1,2,*}, N. Kawakatu², H. Ito³ and H. Nagai²

¹ ISAS/JAXA, 3-1-1 Yoshinodai, 229-8510 Sagami-hara, Japan

² National Astronomical Observatory of Japan, 181-8588 Mitaka, Japan

³ Department of Science and Engineering, Waseda University, Tokyo 169-8555, Japan

Received 30 May 2005, accepted 11 Nov 2005

Published online later

Key words jets – galaxies: active – galaxies: gamma-rays – theory

Gamma-ray emission from cocoons of young radio galaxies is predicted. Considering the process of adiabatic injection of the shock dissipation energy and mass of the relativistic jet into the cocoon, we find that the thermal electron temperature of the cocoon is typically predicted to be of the order of \sim MeV, and is determined only by the bulk Lorentz factor of the jet. Together with the time-dependent dynamics of the cocoon expansion, we find that young cocoons can yield thermal Bremsstrahlung emissions at energies \sim MeV. Hotter cocoons (i.e., GeV) for younger sources are also discussed.

© 2006 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

1 Introduction

Relativistic jets in active galactic nuclei (AGNs) are widely believed to be the dissipation of kinetic energy of relativistic motion with a Lorentz factor of order ~ 10 produced at the vicinity of a super-massive black hole at the galactic center (Begelman, Blandford and Rees 1984 for reviews). The jet in powerful radio loud AGNs (i.e., FR II radio sources) is slowed down via strong terminal shocks which are identified as hot spots. The shocked plasma then expand sideways and envelope the whole jet system and this is so called a cocoon or a bubble (Fig. 1). The cocoon is a by-product of the interaction between AGN jets and surrounding intra-cluster medium (ICM). The internal energy of the shocked plasma continuously inflates this cocoon. So far little attention has been paid to observational feature of the cocoon, since they are usually invisible in GHz bands because of the synchrotron cooling for older electrons.¹ As a result, we just see a part of the cocoon. The visible part is so-called radio lobes in which relatively fresh electrons are filled in. In Fig. 2, we show one good sample of cocoon emission from the powerful radio galaxy Cygnus A for the evidence of its existence.²

* Corresponding author: e-mail: motoki.kino@nao.ac.jp

¹ On the contrary, the emission from the shell made of the shocked ICM (see Fig. 1) has been explored by many authors (e.g., Heinz, Reynolds and Begelman 1998; Sutherland and Bicknell 2007). Since the shells have non-relativistic velocities, the emission from the shells is predicted in the X-ray band.

² The data obtained by Carilli et al. (1991) was re-analyzed to obtain the map shown in Fig. 2. The observation was carried out with VLA A configuration at 330 MHz on 1987 August 18. The data analyzes is performed by standard manner with Astronomical Image Processing System (AIPS). The flux-scale is determined by comparison with 3C 286 and 3C 48 using the AIPS task SETJY. The image is obtained with the DIFMAP after a number of self-calibration iterations.

Among a variety of AGN bubbles, a population so called compact symmetric objects (CSOs) has been widely investigated in various ways (e.g., Fanti et al. 1995; Readhead et al. 1996; O’Dea & Baum 1997; de Vries et al. 1997; O’Dea and Baum 1998; Stanghellini et al. 1998; Snellen et al. 2000; Dallacasa et al. 2000; Giroletti et al. 2003; Nagai et al. 2006; Orienti et al. 2007; Kawakatu et al. 2008). CSOs are smaller than 1 kpc and the previous studies support the youth scenario in which CSOs propagate from pc scales thrusting away an ambient medium and growing up to FR II radio galaxies. CSOs are thus recognized as newly born AGN jets, and they are crucial sources to explore physics of AGN bubbles in their early days.

In this study, we propose that “young AGN bubbles” are a new population of γ -ray emitters in the Universe. The layout of the paper is as follows. We review the expanding cocoon model in §2 following our previous works (Kino and Kawakatu 2005; Kino, Kawakatu and Ito 2007, KK107 hereafter). We show the predicted MeV gamma emission from young cocoons in §3. In §4, we further predict GeV gamma emission for smaller CSOs. Summary and discussion is given in §5.

2 Cocoon inflation by exhausted jet

Here we consider the time-evolution of an expanding cocoon inflated by the dissipation energy of the relativistic jet via terminal shocks. The adiabatic energy injection into the cocoon is assumed. Mass and energy conservation from the jet into the cocoon, which govern the cocoon pressure P_c and mass density ρ_c are written as

$$\frac{\hat{\gamma}_c}{\hat{\gamma}_c - 1} \frac{P_c(t) V_c(t)}{t} \approx 2 T_j^{01}(t) A_j(t) \quad (1)$$

$$\frac{\rho_c(t) V_c(t)}{t} \approx 2 J_j(t) A_j(t), \quad (2)$$

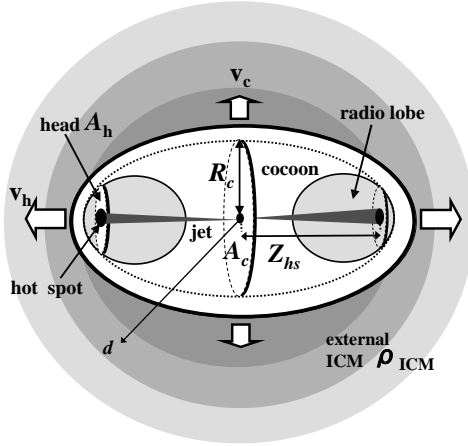


Fig. 1 A cartoon representation of interaction of the ICM with declining atmosphere and the relativistic jet in FR II radio galaxy. As a result, most of the kinetic energy of jet is deposited in the cocoon and it is inflated by its internal energy.

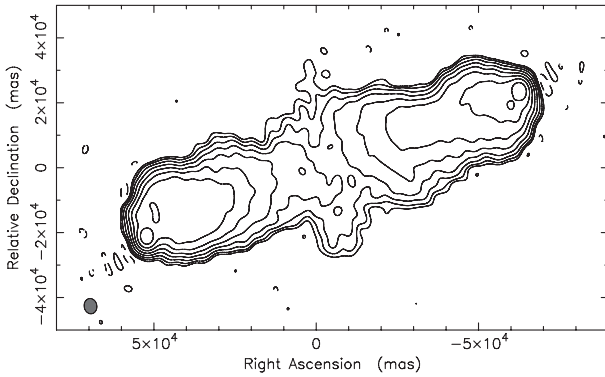


Fig. 2 VLA image of Cygnus A at 330 MHz (A-configuration). The contour level starts with $0.565 \text{ Jy beam}^{-1}$ and increases from there by factors of 2. The convolving beam is $4.73 \times 3.91 \text{ arcsec}$ at the position angle of 10.1° . In this frequency, we can see the synchrotron emission from slightly colder electrons than those emitting GHz ranges. Hence we can identify the cocoon profile which are clearly different from familiar “classical double lobe”.

where $\hat{\gamma}_c$, V_c , T_j^{01} , J_j and A_j , are the adiabatic index of the plasma in the cocoon, the volume of the cocoon, the kinetic energy and mass flux of the jet, and the cross-sectional area of the jet, respectively. The total kinetic energy and mass flux of the jet are $T_j^{01} = \rho_j c^2 \Gamma_j^2 v_j$, $J_j = \rho_j \Gamma_j v_j$ where ρ_j , and Γ_j are mass density and bulk Lorentz factor of the jet (Blandford and Rees 1974). Hereafter we set $v_j = c$. The total kinetic power of the relativistic jet is defined as $L_j \equiv 2T_j^{01}(t)A_j(t)$ and it is assumed to be constant in time.

As for the mass and kinetic energy flux of powerful relativistic jets, numerical simulations tell us that no significant

entrainment of the environmental matter takes place during the jet propagation (e.g., Mizuta et al. 2004). According to this, the mass and kinetic energy flux of the jet are regarded as constant in time. Then, the conditions of $T_j^{01} = \text{const}$, and $J_j = \text{const}$ leads to the relations of $\rho_j(t)A_j(t) = \text{const}$ and $\Gamma_j(t) = \text{const}$. In order to evaluate L_j , we use the shock jump condition of $\Gamma_j^2 \rho_j = \beta_{hs}^2 \rho_{ICM}$ (Kawakatu and Kino 2006) where $\beta_{hs} (= v_{hs}/c)$ and ρ_{ICM} is the advance speed of the hot spot $\beta_{hs} = 10^{-2} \beta_{-2}$ and the mass density of ICM, respectively. Using, the jump condition, L_j is given by

$$L_j = 2 \times 10^{45} R_{kpc}^2 \beta_{-2}^2 n_{-2} \text{ erg s}^{-1} \quad (3)$$

where we use $A_j(t) = \pi R_{hs}^2(t)$, and the hot spot radius R_{hs} is given by $R_{kpc} = R_{hs}(10^7 \text{ yr})/1 \text{ kpc}$. As a fiducial case, we set the number density of the surrounding ICM as $n_{ICM}(d) = \rho_{ICM}(d)/m_p = 10^{-2} \text{ cm}^{-3} n_{-2} (d/30 \text{ kpc})^{-2}$ where d is the distance from the center of ICM and cocoon (see Fig. 1). Since the change of the index from -2 does not change the essential physics discussed in this work, we focus on this case for simplicity. Since L_j is the ultimate source of the phenomena associated with the cocoon, all of the emission powers which will appear in §3 should be less than L_j .

The number density of total electrons in the cocoon is governed by the cocoon geometry and its plasma content. For convenience, we define the ratio of “the volume swept by the unshocked relativistic jet” to “the volume of the cocoon” as $\mathcal{A}(t)$. We denote $V_c(t) = 2(\pi/3)\mathcal{R}^2 Z_{hs}^3(t)$, Z_{hs} satisfies $Z_{hs}(t) = \beta_{hs} ct$, R_c , and $\mathcal{R} \equiv R_c/Z_{hs} < 1$ as the cocoon volume, the distance from the central engine to the hot spot, is the radius of the cocoon body, and the aspect-ratio of the cocoon, respectively (e.g., Kino and Kawakatu 2005). Postulating that \mathcal{R} and Z_{hs}/R_{hs} are constant in time, $\mathcal{A}(t) \equiv \frac{2A_j(t)v_j t}{V_c(t)}$ is evaluated as

$$\mathcal{A}(t) \approx 0.4 \mathcal{R}^{-2} R_{kpc}^2 Z_{30}^{-2} \beta_{-2}^{-1} \quad (4)$$

where $Z_{30} = Z_{hs}(10^7 \text{ yr})/30 \text{ kpc}$. Note that, in the case, the time dependence of \mathcal{A} is deleted since $V_c \propto t^{-3}$ and $A_j \propto t^2$. This case satisfies $v_{hs} = \text{const}$ (e.g., Conway 2002). The cocoon mass density $\rho_c(t)$ is controlled by the mass injection by the jet and it can be expressed as $\rho_c(t) \approx \Gamma_j \rho_j(t) \mathcal{A} = \beta_{hs}^2 \Gamma_j^{-1} \rho_{ICM}(Z_{hs}(t)) \mathcal{A}$ where we use the shock condition of $\Gamma_j^2 \rho_j = \beta_{hs}^2 \rho_{ICM}$. Adopting typical quantities of FR II sources (e.g., Begelman, Blandford and Rees 1984), the number density of the total electrons in the cocoon is given by

$$n_e(t) \approx 4 \times 10^{-5} \bar{\mathcal{A}} n_{-2} \Gamma_{10} \beta_{-2}^2 \left(\frac{t}{10^7 \text{ yr}} \right)^{-2} \text{ cm}^{-3} \quad (5)$$

where $\Gamma = 10\Gamma_{10}$, and $\bar{\mathcal{A}} = \mathcal{A}/0.4$. Here we assume that the mass density of the e^\pm pair plasma is heavier than that of electron-proton one, and then we adopt $\rho_c \approx 2m_e n_e$ in the light of previous works (Reynolds et al. 1996; Wardle et al. 1998; Sikora and Madejski 2000; Kino and Takahara 2004). The upper limit of thermal n_e can be basically constrained by the analysis of Faraday depolarization (Dreher

et al. 1987). However, the strong Faraday depolarization observed in CSOs (Cotton et al. 2003) are likely to be caused by dense foreground matter such as narrow line region. Therefore n_e in radio lobes of CSOs has not been clearly constrained.

Let us estimate the electron (and positron) temperature (T_e) and proton temperature (T_p). From Eqs. (1) and (2) together with the equation of state $P_c \approx 2n_e kT_e$, we can directly derive the temperatures as

$$kT_e \approx 1 \Gamma_{10} \text{ MeV}, \quad kT_p \approx 2 \Gamma_{10} \text{ GeV} \quad (6)$$

where we adopt the two temperatures condition of $kT_e \approx (m_e/m_p)kT_p$. It should be stressed that the temperatures are governed only by Γ_j . It is also worth noting that the geometrical factors in Eqs. (1) and (2) are completely cancelled out. One can naturally understand these properties by comparing the well-established properties such as supernovae and GRBs. Constant temperature in AGN jet can be realized by the “continuous” energy injection into the expanding cocoon whilst temperatures of astrophysical explosive sources such as gamma-ray bursts and supernovae would be decreased because of “impulsive” injection of the energy. Thus the resultant temperatures are uniquely governed by Γ_j and they remain to be constant in time.

3 MeV γ emissions from a young cocoon

3.1 Thermal MeV Bremsstrahlung emission

The time-dependence of the thermal Bremsstrahlung luminosity L_{Brem} is given by $L_{\text{Brem}}(t) \propto n_e^2(t) T_e^{3/2} V_c(t) \propto t^{-1}$ based on the cocoon expansion shown in the previous section. Hence it is clear that a younger cocoons are brighter Bremsstrahlung emitters than older cocoons. In a similar way, brighter synchrotron luminosity has been expected for younger radio galaxies (e.g., Readhead et al. 1996). With relativistic thermal Bremsstrahlung emissivity (Rybicki and Lightman 1979), the luminosity of the optically thin thermal Bremsstrahlung emission νL_ν at energies ~ 1 MeV is estimated as

$$L_{\text{Brem}}(t) \approx 2 \times 10^{40} \bar{n}_e^2 \mathcal{R}^2 \Theta_{10}^{3/2} \left(\frac{t}{10^7 \text{ yr}} \right)^{-1} \text{ erg s}^{-1} \quad (7)$$

Eq. (7) explains the reasons for the non-detection of the thermal emission from older cocoons. One is simply because it is not very bright. The other is because the predicted energy range is ~ 1 MeV, the MeV- γ astronomy is still immature and it is sometimes called as “sensitivity gap” compared with the energy range below 10 keV and above GeV ranges (Takahashi et al. 2004).

In Fig. 3, we show the predicted values of νF_ν for the cocoons with $t = 10^7$ yr and $t = 10^4$ yr located at the distance of $D = 10^2$ Mpc. The cocoon with $t = 10^7$ yr have $\nu F_\nu \sim 10^{-14}$ erg cm $^{-2}$ s $^{-1}$. The detection threshold of SPI instrument on board the INTEGRAL satellite is about $\nu F_\nu \sim 10^{-9}$ erg cm $^{-2}$ s $^{-1}$ at ~ 1 MeV. For a young cocoon with $t = 10^4$ yr, the predicted luminosity is

$\sim 10^3$ times larger than that $\nu F_\nu \sim 10^{-11}$ erg cm $^{-2}$ s $^{-1}$. This is still less than the threshold of INTEGRAL. This may be the reason for the lack of detection of MeV emission from young cocoons up to now. Fig. 3 shows that the XMM/Newton satellites can detect the low energy part of the thermal Bremsstrahlung from young cocoons. In MeV energy band, a proposed mission of detector SGD on board the NeXT satellite with the eye up to ~ 0.6 MeV (Takahashi et al. 2004) could detect the thermal MeV emission from those located slightly closer or younger with smaller Lorentz factor.

3.2 Candidate sources

In order to explore the extended cocoon emission in the X-ray band, one may think it is hard to distinguish overlapping emission from the compact core of the AGN with limited spacial angular resolution of the current X-ray satellites. However, the averaged spectral index in X-ray band (Γ_X) from the compact core of AGNs is softer than the Bremsstrahlung emission (Koratkar and Blaes 1999). Hence it is possible find candidate sources of the MeV cocoon by the value of Γ_X . As far as we know, there are two possible candidates for the Bremsstrahlung emission. Those are B1358+624 (Vink et al. 2006) and PKS B1345+125 (Siemiginowska et al. 2008) actually shows $\Gamma_X \approx 1$, both of them were observed by XMM/Newton. Time variability of observed spectra is also the key to distinguish them. It is obvious that the cocoon emission is constant in time whilst various emissions from the core of AGN should be highly variable. Hence steady emissions are convincingly originated in cocoons.

Intriguingly, “the diffuse X-ray emission” has been indeed detected in PKS B1345+125 with the size of the extended emission is of order ~ 20 kpc by Siemiginowska et al. (2008). The diffuse emission might be associated with the radio lobes of this source. The X-ray emission is elongated towards the South-West similarly to the VLBI jet axis reported by Stanghellini et al. (2001). If the emission is associated with the radio emitting plasma, there are two possibilities to explain the emission. Here we newly stress that the tail of the Bremsstrahlung emission could explain the emission. Based on Eq. (7), the X-ray luminosity of the emission shows $L_X \approx 1 \times 10^{43}$ erg s $^{-1}$. The observed L_X can be explained with the $n_e \approx 1 \times 10^{-2}$ cm $^{-3}$. Based on Eq. (5), the n_e can be realized with $\beta_{\text{hs}} \sim 10^{-1}$ and $n_{\text{ICM}} \sim 10^{-1}$ cm $^{-3}$ for instance. Since the required n_e is considerably large, the analysis of Faraday depolarization will be crucial for checking the upper limit of n_e . The other possibility is non-thermal emissions from the lobes which is recently investigated by Stawarz et al. (2008). Observations near the peak of thermal emission NeXT satellite will be crucial to distinguish whether the emission is thermal or non thermal one.

4 Younger radio sources as “hotter” bubbles

So far, we discuss the cocoon property in the phase of no significant cooling. The phase roughly corresponds to medium size symmetric objects (MSOs) and FR II galaxies. Since cooling timescales become shorter for smaller sources, cooling effects for CSOs are more effective than the case for larger ones such as MSOs and FR IIs. We consistently solve a set of equations which describes young bubble expansions including the effects of Bremsstrahlung emission and adiabatic loss together with the initial conditions indicated by CSO observations. Then we find that the bubbles have electron temperature of $\sim \text{GeV}$ at initial phases, the bubbles then cooled down to MeV by the adiabatic loss. We further estimate these γ -ray emissions and show that it could be detected with Fermi (GLAST) (Kino et al. 2009).

5 Summary and discussion

We have investigated the luminosity evolutions of AGN cocoons together with the dynamical evolution of expanding cocoon. Below we summarize the main results of the present work.

1. We newly predict the Bremsstrahlung emission peaked at MeV- γ band as a result of standard shock dissipation of relativistic jets in AGNs. The temperature of the cocoon is governed only by the bulk Lorentz factor of the jet Γ_j . The electron temperature T_e relevant to observed emissions is typically predicted in the range of MeV for $\Gamma_j \sim 10$. Constant temperatures of plasma in the cocoon can be realized because of the continuous energy injection by the jet with constant Γ_j (KKI07).
2. We further investigate younger bubble expansions including the effects of Bremsstrahlung emission and adiabatic loss together with the initial conditions of CSOs. Then we find that the lobes initially have electron temperature of GeV and the lobes then cool down to MeV by the adiabatic loss. The γ -ray emissions could be detected with Fermi (GLAST) (Kino et al. 2009).

Acknowledgements. We would like to thank C. R. Kaiser and M. Sikora for valuable comments. NK is supported by Grant-in-Aid for JSPS Fellows. HI acknowledge the Grant for Special Research Projects at Waseda University.

References

Begelman, M. C., Blandford, R. D., Rees, M. J., 1984, *Rev. Mod. Phys.*, 56, 255
 Blandford, R. D., Rees, M. J., 1974, *MNRAS*, 169, 395
 Carilli, C. L., Perley, R. A., Dreher, J. W., Leahy, J. P., 1991, *ApJ*, 383, 554
 Cotton, W. D., et al., 2003, *PASA*, 20, 12
 Dallacasa, D., Stanghellini, C., Centonza, M., Fanti, R. 2000, *A&A*, 363, 887
 De Vries, W. H., Barthel, P. D., O’Dea C. P., 1997, *A&A*, 321, 105
 Dreher, J. W., Carilli, C. L., Perley, R. A., 1987, *ApJ*, 316, 611

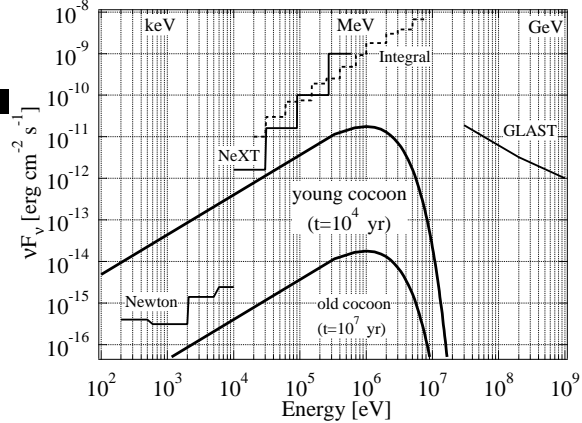


Fig. 3 Model prediction of MeV-peaked thermal bremsstrahlung emission from cocoons located at $D = 10^2$ Mpc. The predicted emission from young cocoon is brighter enough to detect in X-ray band whilst that from an old cocoon is much darker than the detection limits.

Fanti, C., Fanti, R., Dallacasa, D., Schilizzi, R.T., et al. 1995, *A&A*, 302, 317
 Giroletti M., Giovannini G., Taylor G. B., Conway J. E., Lara L., Venturi T., 2003, *A&A*, 399, 889
 Guainazzi, M., Siemiginowska, A., Stanghellini, C., Grandi, P., Piconcelli, E., Azubike Ugwoke, C., 2006, *A&A*, 446, 87
 Gugliucci, N.E., Taylor, G.B., Peck, A.B., Giroletti, M. 2005, *ApJ*, 622, 136
 Heinz, S., Reynolds, C. S., Begelman, M. C., 1998, *ApJ*, 501, 126
 Kawakatu, N., Kino, M., 2006, *MNRAS*, 370, 1513
 Kawakatu, N., Nagai, H., Kino, M., 2008, *ApJ*, 687, 141
 Kino, M., Takahara, F., 2004, *MNRAS*, 349, 336
 Kino, M., Kawakatu, N., 2005, *MNRAS*, 364, 659
 Kino, M., Kawakatu, N., Ito, H., 2007, *MNRAS*, 376, 1630 (KKI07)
 Kino, M., Ito, H., Kawakatu, N., Nagai, H., 2009, *MNRAS*, submitted (arXiv:0812.1850)
 Koratkar A., Blaes O., 1999, *PASP*, 111, 1
 Mizuta, A., Yamada, S., Takabe, H., 2004, *ApJ*, 606, 804
 Nagai, H., Inoue, M., Asada, K., Kamenoi, S., Doi, A., 2006, *ApJ*, 648, 148
 O’Dea, C. P., Baum, S. A., 1997, *AJ*, 113, 148
 O’Dea, C. P., Mu, B., Worrall, D. M., Kastner, J., Baum, S., de Vries, W. H., 2006, *ApJ*, 653, 1115
 Orienti, M., Dallacasa, D., Stanghellini, C. 2007, *A&A*, 475, 813
 Polatidis, A.G., Conway, J.E. 2003, *PASA*, 20, 69
 Readhead, A. C. S., Taylor, G. B., Pearson, T. J., Wilkinson, P. N., 1996, *ApJ*, 460, 634
 Reynolds, C. S., Fabian, A. C., Celotti, A., Rees, M. J., 1996, *MNRAS*, 283, 873
 Siemiginowska, A., LaMassa, S., Aldcroft, T. L., Bechtold, J., Elvis, M., 2008, *ApJ*, 684, 811
 Snellen, I.A.G., Schilizzi, R.T., Miley, G.K. et al. 2000, *MNRAS*, 319, 445
 Stanghellini C., O’Dea C. P., Dallacasa D., Baum S. A., Fanti R., Fanti C., 1998, *A&AS*, 131, 303
 Stanghellini, C., Dallacasa, D., O’Dea, C. P., Baum, S. A., Fanti, R., Fanti, C., 2001, *A&A*, 377, 377
 Stawarz, Ł., Ostorero, L., Begelman, M. C., Moderski, R., Kataoka, J., Wagner S., 2008, *ApJ*, 680, 911

- Sutherland, R. S., Bicknell, G. V., 2007, *ApJS*, 173, 37
Takahashi, T., et al., 2004, *NewAR*, 48, 269
Vink, J., Snellen, I., Mack, K.-H., Schilizzi, R., 2006, *MNRAS*,
367, 928
Wardle, J. F. C., Homan, D. C., Ojha, R., Roberts, D. H., 1998,
Nature, 395, 457