Accretion Disks, Jets and Blazar Variability

Paul J. Wiita

Department of Physics and Astronomy, Georgia State University,
Atlanta GA 30302-4106, USA

Abstract. Although blazar variability is probably dominated by emission from relativistic jets, accretion disks should be present in all blazars. These disks produce emission over most of the electromagnetic spectrum; various unstable processes operate in those disks which will lead to variable emission. Here I summarize some of the most relevant disk mechanisms for AGN variability. I also discuss some aspects of jet variability, focusing on the possibility that ultrarelativistic jets of modest opening angle can reconcile TeV blazar emission with the many subluminal VLBI knots seen in those sources. Finally, I present recently illuminated characteristics of optical microvariability of different classes of AGN which have important implications for the dominant processes involved.

1. Introduction

Regardless of the exact fashion in which the jets which dominate blazar spectra are launched (e.g. Vlahakis, these proceedings; Meier, these proceedings; Hardee, these proceedings), all plausible models require them to either be anchored in accretion disks or to emerge from the immediate vicinity of black holes which are accreting. Most modes of accretion produce significant fluxes from the disks themselves, and most of those emissions will be variable. There are two key questions with respect to accretion disks and blazar variability. Can these disk emissions ever compete with the jet emissions so as to make detectable contributions? Can variations from these disks occur on timescales short enough to be detected over the timespans we are able to observe blazars? In this brief review I concentrate on these questions but also address a couple of specific points related to blazar jets. Czerny’s (2004) recent review also covers many aspects of accretion disks that will be stressed here; Czerny also provides nice discussions of other aspects of AGN variability not covered here and additional references. Key observations and basic theoretical points about disks are summarized in §§2–4. Aspects of blazar jets are discussed in §5 and results and implications of new optical microvariability studies of different AGN classes are noted in §6.

2. Contributions from Accretion Disks to AGN Spectra

The most direct evidence for accretion disk (hereafter AD) emission comes from the quasi-thermal big blue bumps sometimes seen in AGN spectra, which are otherwise roughly characterized by power-law spectral energy distributions in the IR–UV. While these bumps are not uncommon in quasars, their presence in blazars is rare, presumably because the disk emission is usually swamped.
by the boosted nearly power-law continuum. New quasi-simultaneous multi-
band observations of the blazar AO 0235+164 (Raiteri et al. 2005) do provide
such strong evidence for a big blue bump. Additional recent evidence for AD
emission in several quasars comes from the detection of an optically thick Balmer
dge revealed in the polarized emission (e.g. Ton 202; Kishimoto et al. 2004).
Other types of direct observational evidence for flattened geometries, presumably
related to ADs, include the broad Fe Kα lines seen in Narrow Line Seyfert 1
galaxies (e.g. Reynolds & Nowak 2003) and the variable double peaked emission
lines seen in a substantial fraction of quasar spectra (e.g. Strateva et al. 2003).

The now fairly well accepted picture for accretion flows indicates that the
relative thickness of an AD and its extent toward its central black hole (BH) are
predominantly determined by its accretion rate, \( \dot{M} \). For accretion flows where
the accretion luminosity, \( L \), is comparable to the Eddington limit, \( L/L_E \sim 1 \)
(\( L_E \simeq 1.3 \times 10^{46} \dot{M}_8 \) ergs s\(^{-1} \), with \( \dot{M}_8 = 10^8 M_8 \)M\(_8\)), the disk becomes geo-
metrically and optically thick (e.g. Paczyński & Wiita 1980) and the inner edge
of the disk is inside the marginally stable orbit. These bloated “Polish donuts”
are quite inefficient radiators, since much of the ample quasi-thermal radiation
they produce is trapped within the AD and swept through the event horizon.
For flows where \( L/L_E \sim 0.1 \) the “standard” geometrically thin, but optically
thick, AD picture (e.g. Shakura & Sunyaev 1973) basically holds. For these,
the most extensively studied class of AD, the inner edge is at the marginally
stable orbit (\( r_{ms} = 6GM_{BH}/c^2 \equiv 3r_s \) for a Schwarzschild BH) and the efficiency
of mass to radiation conversion is high (\( > 0.057 \)) since most of the radiation
produced in the AD escapes.

At sufficiently low accretion rates, producing \( L/L_E < 0.01 \), a two tempera-
ture flow is likely to develop (e.g. Rees et al. 1982); here the ions in the infalling
plasma can reach virial temperatures, but their low densities mean that they fall
into the BH before they can share their energy with the electrons, which do the
bulk of the radiating. There are various possible detailed structures for such low
\( \dot{M} \) flows (e.g. Chakrabarti 1996), but they are often generically called ADAs
(for Advection Dominated Accretion Flows; e.g. Chen et al. 1995). These flows
are characterized by a transition radius, \( r_t > r_{ms} \), inside of which the flow is
generically thick but optically thin, and outside of which it is physically thin
but optically thick.

The common view is that AGN involve the first two categories of accretion
flows with the thin disk category most common. On the other hand, starved
BHs, such as the one in our Galactic nucleus, are of the last type. Less well
accepted, but certainly possible, is the hypothesis that intermediate luminosity
AGN, such as radio galaxies and normal Seyfert galaxies, may also have thin
disks which terminate at \( r \sim 100r_s \) (see Czerny 2004 and references therein). It
should be stressed that any particular galactic nucleus may (and probably does)
behave different accretion modes at different times in its history and therefore
can evolve from inactive, to one type of AGN, to another type of AGN.

3. Timescales for Accretion Disk Variability

If one adopts cylindrical coordinates, \((r, z, \phi)\), assumes a quasi-Keplerian flow,
and expresses distances in terms of the Schwarzschild radius, \( r_s \), so that
Accretion Disks, Jets and Variability

$R \equiv r/r_s$, one finds that the dynamical timescale in an AD is nearly the same as for a Keplerian orbit, and so is

$$t_{\text{dyn}} = 2 \times 10^3 R^{3/2} M_8 \text{ s.} \quad (1)$$

Thus one should not observe variations faster than a few minutes for relatively low mass AGN (with $M_8 < 0.1$) or faster than several hours for very massive AGN (with $M_8 > 10$) if there are no bulk relativistic motions. Such fast variations associated with ADs would demand perturbations that affect a significant portion of the inner part of a disk and form and decay on orbital timescales.

Perhaps a more realistic timescale for many physical variations would be associated with the time needed for a sound wave to be transmitted across a radial region of extent $r$ for a disk of thickness $h$, $t_{\text{sound}} \simeq t_{\text{dyn}}(r/h)$; this is roughly an order of magnitude greater than $t_{\text{dyn}}$ for thin AD models.

Another key timescale on which one would expect to see changes in any AD is its thermal timescale, $t_{\text{th}}$, defined as the ratio of the disk’s internal energy to the heating or cooling rate. If, for simplicity, we assume the Shakura–Sunyaev $\alpha$-disk parameterization, where the shear stress is related to the total pressure by the expression $T_r \phi \equiv \alpha P$, then the thermal timescale is

$$t_{\text{th}} = t_{\text{dyn}}/\alpha = 2 \times 10^4 \alpha_{-1}^{-1} R^{3/2} M_8 \text{ s,} \quad (2)$$

where a typical value of $\alpha = 0.1 \alpha_{-1}$ has been used. These thermal timescales are of the order of days for $10^8 M_\odot$ BHs and are comparable to $t_{\text{sound}}$.

One of the most interesting longer timescales is related to the rate at which matter flows through the AD. This viscous timescale is simple to estimate if we stick to the $\alpha$-disk approximation (e.g. Czerny 2004):

$$t_{\text{visc}} \simeq t_{\text{th}} \left(\frac{R}{h}\right)^2 = 2 \times 10^6 \alpha_{-1}^{-1} \left(\frac{r}{h}\right)^2 R^{3/2} M_8 \text{ s,} \quad (3)$$

where we have assumed a typical value of $h = 0.1 h_{-1}$. Thus, substantial variations in flux over months to years (for $M_8 \sim 1$), could be related to viscous processes.

If there is an ADAF, with a hot inner flow and a cold outer disk, or if there is a strong X-ray producing corona sandwiching a standard thin disk, then the transition radius, $r_t$, may slowly change with time, either by evaporation or by a significant outflow of gas. The key question becomes: how fast can the cold disk be removed? In either event, the disk temperature must rise to roughly the virial temperature, and enough energy to perform this heating must be stored up in the disk. For an $\alpha$-disk, this gives $t_{\text{evap}} \equiv t_{\text{visc}}$, but more generally and realistically it can be shown that (Czerny 2004)

$$t_{\text{evap}} \simeq 1000 \left(\frac{r_t}{100 r_s}\right)^2 \dot{m}_{-1} M_8 \text{ yr,} \quad (4)$$

where the accretion rate, $\dot{m}_{-1}$ has been normalized to 0.1 of that needed to produce $L_E$: $\dot{m} \equiv \dot{M}/\dot{M}_E$. For reasonable values of $r_t$, such variations could only be relevant (over the decadal periods we can observe AGN) for relatively low values of BH mass or $\dot{M}$, such as those associated with Seyferts. But given
The massive galactic hosts of most blazars (at least for $z > 0.5$; Kotilainen et al. 2005) and the nearly linear relation between galactic halo mass and that of the central BH, this timescale is likely to exceed $10^3$ yr for blazars.

The longest interesting timescale, $t_{fuel}$, is that over which the accretion rate changes through differences in the amount of gas available to the BH. While an occasional gas bolus may be come from a star disrupted in the vicinity of the BH, the fundamental availability time is comparable to the lifetime of the AGN phenomenon itself. Fueling should be driven by processes related to galactic mergers or harassment and will typically be $t_{fuel} \sim 10^7$–$10^8$ yr.

4. Physical Mechanisms for Accretion Disk Variability

The radiation pressure instability has long been known to afflict $\alpha$-disks (Shakura & Sunyaev 1976). Since AGN ADs should be radiation pressure dominated over substantial ranges in $r$ and $\dot{M}$ this instability should yield fluctuations in emission, although it is unlikely to disrupt the disk. Recent simulations of these variations produce substantial flares on timescales of $t_{visc} \sim 100 r_s$ (e.g. Teresi et al. 2004). This class of variation may be the appropriate explanation for fluctuations in the microquasar GRS 1915+105 (Teresi et al. 2004) over minute timescales. If scaled to AGN masses, the radiation pressure instability may yield big AD outbursts from the X-ray through IR over years to decades.

The magneto-rotational instability (MRI) is now commonly agreed to be present in all ADs (e.g. Balbus & Hawley 1991). The MRI rapidly amplifies seed magnetic fields and is very likely to provide the dominant viscosity in most ADs, providing an effective, but fluctuating, $\alpha \sim 0.01$–0.1 (e.g. Armitage 1998; Miller & Stone 2000). These MRIs will produce strong turbulence which can yield significant changes in both the production of heat energy and effective $\dot{M}$ on rapid (a few $t_{dyn}(r_{ms})$) timescales, or hours for a $10^8 M_\odot$ BH, as shown by recent simulations (Armitage & Reynolds 2003). While they should also produce some disk clumping and some larger variations on longer timescales, the MRI is unlikely to destroy the disk. Changes in line profiles associated with ADs also may be produced by MRI.

The double-humped emission lines detected in $\sim 10\%$ of AGN spectra (e.g. Strateva et al. 2003) are frequently observed to show changes in the relative heights of the red and blue humps. These changes, and the shapes of the features themselves, are best explained by spiral shocks in ADs (Chakrabarti & Wiita 1994). The perturbation of a disk by a smaller BH in the vicinity of the AD can efficiently drive these shocks. These spiral shocks can also produce factor of a few variations in the AD emission on the orbital timescales of the perturbers, which, however, would typically be decades or longer (Chakrabarti & Wiita 1993).

Because ADs are almost certainly magnetized, there is a high probability that they are sheathed by coronae, which are certain to contribute substantially to the X-ray emission and should have some role to play in other bands. While understanding of coronal structure formation above ADs is still a long way off, simulations of MRI do illustrate the formation of large loops over the course of several $t_{dyn}$ (e.g. Miller & Stone 2000). These coronal structures probably play a significant part in the X-ray emission and variability of Seyfert galaxies, but their importance for quasars and blazars is much less clear. The variations in
energy that can be released from coronal flares are probably too small to be detected, particularly outside the X-ray band, in that individual flares are limited in their powers (e.g. Krishan et al. 2003). Still, large groups of coordinated flares, produced by an avalanche mechanism or other form of self-organized-criticality (e.g. Mineshige et al. 1994) can produce the optical power-spectrum density observed in many AGN (Xiong et al. 2000).

5. Jets and Blazar Variability

As this key topic is the focus of many other papers in this volume, including those by M. Aller, Böttcher, Georganopoulos, Joshi, and Kazanas, here I make only a few general points. My focus is on two questions: Is there a need for coherent emission from blazar jets? Can subluminal VLBI motions be reconciled with TeV emission from blazars?

Clearly, relativistic shocks propagating down jets can explain much of the gross radio through optical variations via boosted synchrotron emission. Turbulence, instabilities, and magnetic inhomogeneities can probably explain the bulk of rapid variations. The inverse Compton (IC) mechanism, invoked either through synchrotron self-Compton, external Compton, or decelerating jets can explain particular observed high energy variations with respect to low energy ones. Still, no relatively simple model seems able to explain most broad band observations, and perhaps multiple sources of IC seed photons are needed.

Compact radio sources with intrinsic brightness temperatures, $T_{B,\text{int}} > 10^{11}$K exceed the self-absorbed source IC catastrophe limit (Singal & Gopal-Krishna 1985). Early observations of intraday variability (IDV) at cm-wavelengths seemed to imply $T_B \sim 10^{21}$K. Bulk relativistic motions with very high Lorentz factors ($\Gamma \equiv (1 - \beta^2)^{-1/2} \sim 10^3$) are required to bring these into accord, as a factor of $\Gamma^3$ converts the intrinsic $T_B$ into the observed one. While these huge $\Gamma$ factors prevent the production of too many X-rays, they do so at the cost of very low synchrotron radiative efficiencies, and thus demand very high jet powers. This problem seemed to go away when later observations showed that most IDV is due to refractive interstellar scintillation (e.g. Kedziora-Chudczer et al. 2001); then $T_{B,\text{int}} \sim 10^{15}$K so modest $\Gamma$'s ($\sim 30$) remove the catastrophe. But a recent unpublished claim that the blazar J1819+3845 shows diffractive scintillation with a size $< 10\mu$as (Macquart & de Bruyn 2005) implies $T_{B,\text{int}} \gg 10^{14}$K; if true, $\Gamma > 10^3$ is needed to allow incoherent synchrotron emission.

Coherent radiation induced by strong Langmuir turbulence in AGN jets can produce the needed huge $T_B$'s without requiring such extreme Lorentz factors (e.g. Krishan & Wiita 1990), but such coherent models (implicitly) assume $\nu_{\text{plasma}} > \nu_{\text{cyclotron}}$. Recently Begelman et al. (2005) have argued that the opposite is much more likely to be the case in blazar jets. Begelman et al. (2005) propose that many transient small-scale magnetic mirrors can be produced from hydromagnetic instabilities, shocks or turbulence. The electrons accelerated along these converging flux tubes can quite naturally produce the population inversion needed for a cyclotron maser. Fundamentally, this class of maser is pumped by turning kinetic and magnetic energy into $\vec{j} \cdot \vec{E}$ work. If future observations do wind up supporting the need for coherent emission processes in blazars, this cyclotron maser mechanism appears to be quite promising.
The only semi-direct probe of extragalactic jet speed comes from VLBI knot apparent motions, and quite surprisingly, > 30% of these turn out to be subluminal (\(\beta_{\text{app}} < 1\)) for TeV emitting blazars (Piner & Edwards 2004). On the other hand, to avoid excessive photon-photon collisions, these TeV blazars require ultrarelativistic jets (Krawczynski et al. 2002) with \(15 < \delta < 100\); \(\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}\), with \(\theta\) our viewing angle to the jet. Taking into account IR background absorption strongly implies \(45 < \delta\) (Kazanas, these proceedings). And, while rare (Lister, these proceedings) some \(\beta_{\text{app}} > 25\) components are seen in EGRET blazars (Piner et al., these proceedings).

Several ways have been proposed to reconcile the high \(\delta\) factors with low apparent speeds. The leading idea is that jets might have fast cores (spines) which give rise to the \(\gamma\)-ray emission via IC while slower outer layers (sheaths) produce the radio knot emission (e.g. Ghisellini et al. 2005). Alternatively, jets could rapidly decelerate between sub-pc (\(\gamma\)-ray) and pc (VLBI knot) scales (Georganopoulos, Kazanas, these proceedings). Also, a few such cases could arise from viewing angles to within \(\sim 1^\circ\), but there are too many slow knots for this to be the main explanation. Finally, it must be recalled that some of the motions may reflect pattern, not physical, speeds (Hardee, these proceedings).

We (Gopal-Krishna et al. 2004) have recently shown another way to reconcile the very high \(\Gamma\)s preferred by IC and variability arguments with the low \(\beta_{\text{app}}\) values seen in TeV blazar jets. Instead of assuming that the jets are cylindrical as was done in all previous models, we allow them to have small opening angles, \(\omega\). The resulting slightly different viewing angles to the finite jet emitting region require the computation of weighted fluxes and weighted \(\beta_{\text{app}}\) values. The apparent transverse speeds peak at lower values and at significantly higher \(\theta\) than for cylindrical jets (upper panels, Fig. 1). We find many sources with \(\beta_{\text{app}} < 1\) and only a few with \(\beta_{\text{app}} \sim \Gamma\) if \(\Gamma > 25\) and \(\omega > 5^\circ\) (lower panels, Fig. 1).

Figure 1. The upper panels give distributions of \(\beta_{\text{app}}\) vs. \(\theta\) for \(\Gamma = 10, 50\) and 100. Results for jet opening angles, \(\omega = 0^\circ, 1^\circ, 5^\circ\) and 10° are labeled. The lower panels show the cumulative probabilities for \(\beta_{\text{app}} > \beta\) for the same values of \(\Gamma, \theta\) and \(\omega\). From Gopal-Krishna et al. (2004); copyright, AAS
6. No Fundamental Difference Between Blazars and All Other AGN?

We have recently completed an extensive monitoring campaign of optical microvariability for a group of 25 powerful AGN (Gopal-Krishna et al. 2003; Sagar et al. 2004; Stalin et al. 2004a,b). This program involved sets, matched in optical luminosity and redshift, of: radio-quiet quasars (RQQs); lobe-dominated radio-loud quasars (LDQs); core-dominated radio-loud quasars (CDQs); and BL Lacertae objects (BLLs). In the standard unified scheme, the first two groups should not be affected by beaming, but the latter two would be called blazars. Although there had been various earlier microvariability studies also using CCD differential photometry of most of these different classes, discrepant results were reported, particularly for RQQs. I believe all earlier results were suspect, because of poor choices of objects, comparison stars, observing techniques, or data reductions. We are confident that our observing techniques, which always involved at least 4 hours of frequent monitoring per source per night, along with our careful reductions, have often provided highly significant detections of variations as small as \( \sim 0.01 \) mag over the course of several hours.

One main result of this work is to confirm that BL Lacs (and the one high-polarization CDQ in our sample) show a high duty cycle for microvariability (\( \sim 60\% \)). These blazars showed variations of up to \( \sim 0.14 \) mag in the course of a single night (Sagar et al. 2004).

A more important result was the first clear detection of microvariability on several nights for different RQQs (Gopal-Krishna et al. 2003; Stalin et al. 2004a). Furthermore, the duty cycles for RQQs, LDQs and (low-polarization) CDQs were all \( \sim 20\% \) (Stalin et al. 2004a,b). All of the observed microvariations for these non-blazars ranged between 0.01 and 0.03 mag. The properties of the microvariability in RQQs and LDQs were indistinguishable in our studies, which would be unexpected if these optical variations were arising in jets, in that the RQQs were all very weak in the radio band. Our original motivation for searching for RQQ microvariability was the expectation that, if any were found, it could be logically attributed to AD fluctuations.

Still, all of these new results can be understood in terms of the standard beaming picture, where the BLLs and high-polarization CDQs are viewed at small angles to the line-of-sight and the RQQs and LDQs are viewed at larger angles. The Doppler enhancement of the amplitude of the variations and the Lorentz time-dilation for sources viewed at small \( \theta \) together can provide for the higher duty cycles and more powerful amplitude distributions of microvariability for the blazars, even if their rest-frame characteristics are identical to those of the non-blazars (Gopal-Krishna et al. 2003; Stalin et al. 2004a).

One possible explanation of this microvariation unification is that all these classes of AGN do possess jets, which, on sufficiently small scales, yield fluctuations which are seen in the optical; however, in RQQs these jets are somehow quenched before significant radio emission is produced. Another possibility is that these fluctuations do originate in the ADs, and are seen unbeamed from non-blazars; in the case of blazars these fluctuations propagate into jets launched from the ADs and are amplified by the relativistic motion. Additional observations will be needed to distinguish between these hypotheses.
7. Conclusions

Accretion disks exist in all AGN, including blazars. They can contribute noticeable amounts to the fluxes emerging from blazars, at least in the IR–X-ray bands. Since ADs must vary on timescales we can observe, some fraction of detected blazar variability can arise from ADs. There are several ways to reconcile low VLBI knot speeds with high Lorentz factors in TeV blazars; if several degree opening angles are present, no variations in jet speed are necessary to do so. Microvariability of RQQs and blazars can be interpreted as arising from the same process; this either implies that jets are present in all AGN or that variations produced in a disk may be carried into, and amplified by, jets.

Acknowledgments. I thank my collaborators, G. Bao, P. Barai, S. K. Chakrabarti, S. Dhurde, Gopal-Krishna, V. Krishan, S. Ramadurai, R. Sagar, C. S. Stalin and Y. Xiong. I am most grateful for hospitality at Princeton University and acknowledge support from NASA, NSF and RPE funds at GSU.

References

Armitage, P. J. 1998, ApJ, 501, L189
Armitage, P. J., & Reynolds, C. S. 2003, MNRAS, 341, 1041
Balbus, S. A., & Hawley, J. F. 1991, ApJ, 376, 560
Begelman, M. C., & Rees, M. J. 2005, ApJ, in press (astro-ph/0502151)
Chakrabarti, S. K. 1996, ApJ, 464, 664
Chakrabarti, S. K., & Wiita, P. J. 1993, ApJ, 411, 602
Chakrabarti, S. K., & Wiita, P. J. 1994, ApJ, 434, 518
Chen, X., Abramowicz, M. A., Lasota, J.-P., Narayan, R., & Yi, I. 1995, ApJ, 428, L61
Czerny, B. 2004, in AGN Variability from X-rays to Radio, in press (astro-ph/0409254)
Ghisellini, G., Tavecchio, F., & Chiaberge, M. 2005, A&A, 432, 401
Gopal-Krishna, Dhurde, S. & Wiita, P. J. 2004, ApJ, 615, L81
Gopal-Krishna, Stalin, C. S., Sagar, R., & Wiita, P. J. 2003, ApJ, 586, L25
Kedziora-Chudczer, L. L., et al. 2001, MNRAS, 325, 1411
Kishimoto, M., Antonucci, R., Boisson, C., & Blaes, O. 2004, MNRAS, 354, 1065
Kotilainen, J. K., Hyvönen, T., & Falomo, R. 2005, A&A, in press (astro-ph/0505443)
Krawczynski, H., Coppi, P. S., & Aharonian, F., 2002, MNRAS, 336, 721
Krishan, V., & Wiita, P. J. 1990, MNRAS, 246, 597
Krishan, V., Ramadurai, S. & Wiita, P. J. 2003, ApJ, 584, L25
Krishan, V., & Wiita, P. J. 2005, MNRAS, 350, 175
Liller, K. A., & Stone, J. M. 2000, ApJ, 534, 398
Mineshige, S., Ouchi, B. N., & Nishimori, H. 1994, PASJ, 46, 97
Paczynski, B., & Wiita, P. J. 1980, A&A, 88, 23
Piner, B. G., & Edwards, P. G. 2004, ApJ, 600, 15
Raiteri, C. M., et al. 2005, A&A, in press (astro-ph/0503312)
Rees, M. J., Phinney, E.S., Begelman, M.C., & Blandford, R.D. 1982, Nature, 295, 17
Reynolds, C. S., & Nowak, M. A. 2003, Phys. Rep. 377, 389
Sagar, R., Stalin, C. S., Gopal-Krishna, & Wiita, P. J. 2004, MNRAS, 348, 176
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Shakura, N. I., & Sunyaev, R. A. 1976, MNRAS, 175, 613
Singal, K. A., & Gopal-Krishna 1985, MNRAS, 215, 383
Stalin, C. S., Gopal-Krishna, Sagar, R., & Wiita, P. J. 2004a, MNRAS, 350, 175
Stalin, C. S., Gopal-Krishna, Stalin, C. S., & Wiita, P. J. 2004b, JApA, 25, 1
Strateva, I. et al. 2003, AJ, 126, 1720
Teresi, V., Molteni, D., & Toscano, E. 2004, MNRAS, 351, 297
Xiong, Y., Wiita, P. J., & & Bao, G. 2000, PASJ, 52, 1097