The Astrophysical Journal, 499:L27–L30, 1998 May 20

WARPED DISKS AS A POSSIBLE ORIGIN OF TORQUE REVERSALS IN ACCRETION-POWERED PULSARS

M. H. van Kerkwijk,[1] Deepto Chakrabarty,[2] J. E. Pringle,[1,3] and R. A. M. J. Wijers[1]

Received 1998 February 12; accepted 1998 March 24; published 1998 April 28

ABSTRACT

Enigmatic transitions between spin-up and spin-down have been observed in several X-ray pulsars accreting matter via an accretion disk. In these transitions, the torque changes sign but remains at nearly the same magnitude. It has been noted previously that alternating prograde and retrograde disk flows would explain many features of the torque reversals, although it has been unclear how a stable retrograde disk could be formed. We suggest that the reversals may be related to the disk at times being warped to such an extent that the inner region becomes tilted by more than 90°. This region would thus become retrograde, leading to a negative torque. Accretion disk models can show such behavior, if account is taken of a warping instability due to irradiation. The resulting "flip-overs" of the inner parts of the disk can reproduce most characteristics of the observations, although it remains unclear what sets the timescale on which the phenomenon occurs. If this model were correct, it would have a number of ramifications, for instance, that in the spin-down state, the X-ray source would mostly be observed through the accretion disk.

Subject headings: accretion, accretion disks — binaries: close — pulsars: individual (Centaurus X-3, GX $1+4$, OAO $1657-415$, 4U $1626-67$) — stars: neutron — X-rays: stars

1. INTRODUCTION

Long-term, continuous monitoring by the BATSE all-sky monitor on the *Compton Gamma Ray Observatory* has led to a qualitative change in our picture of the spin-frequency behavior of accreting X-ray pulsars (Bildsten et al. 1997, hereafter B97). Of the four well-measured persistent sources thought to accrete by way of an accretion disk, all display sudden transitions between episodes of steady spin-up and spin-down. The spin change rate (i.e., the absolute value of the pulse-frequency derivative) is nearly equal for spin-up and spin-down, and it is comparable to the torque expected if all the angular momentum of the accreting gas is deposited at the magnetospheric boundary and transferred to the neutron star. In at least some of these systems, however, Roche lobe overflow is thought to occur, and hence the matter inserted into the accretion disk has only one sense of angular momentum; symmetric torque reversals would thus not be expected.

Previous accretion torque models, in which the net torque could be positive or negative depending on the mass accretion rate $\dot{M}$ (e.g., Ghosh & Lamb 1979), cannot easily reproduce the observations (see Nelson et al. 1997). We only list the main arguments here: (i) one needs stepwise changes in $\dot{M}$ to produce distinct spin-up and spin-down states—this seems unlikely; (ii) one would expect changes in $\dot{M}$ to be reflected in the X-ray luminosity L_X—there are variations in L_X, but these appear uncorrelated with the spin-up/down state; and (iii) one expects at all times a positive correlation between torque and luminosity—for GX $1+4$, an anticorrelation is observed during its spin-down state (Chakrabarty et al. 1997b).

Suggestions about a possible cause for the torque reversals have been made by Yi, Wheeler, & Vishniac (1997) and Nelson et al. (1997). Yi et al. (1997) suggested that the reversals were due to small changes in $\dot{M}$ around a critical value at which the system changes from a primarily Keplerian flow to a substantially sub-Keplerian, radially advective flow. This addresses points (i) and (ii), but not point (iii).

Nelson et al. (1997) explored the possibility of having systems in which nothing changes except the sense of rotation of the disks. They found that this would explain the observations very well. They quoted a suggestion by Makishima et al. (1988) that in GX $1+4$, one might have accretion from a wind and thus form a retrograde disk more easily. As Nelson et al. noted, however, it is very hard to imagine how a stable retrograde disk could form, especially in the ultracompact binary 4U $1626-67$, for which all indications are that the mass transfer is by Roche lobe overflow from a very low mass companion.

Here we suggest a modification of the Nelson et al. picture, viz., that it is only the inner part of the disk that is changing its sense of rotation, as a consequence of very strong warping of the disk. Accretion disks are unstable to warping if lit strongly by a central radiation source (Pringle 1996). In numerical simulations that include such irradiation, the disk can sometimes become more and more warped, until the inner part has become inclined by well over 90° (Pringle 1997; see Fig. 6 of that paper for illustrations of a disk with its inner parts flipped over).

In § 2, we give an updated summary of the observations. In § 3, we briefly discuss the warping process and describe simulations done specifically for X-ray binaries. We proceed to make a qualitative comparison with the observations and to discuss ramifications. We summarize our conclusions in § 4.

2. SUMMARY OF OBSERVATIONS

BATSE has monitored five persistent, disk-fed accreting X-ray pulsars for nearly 7 yr (B97). Here we summarize the observations for four of these. We exclude Her X-1, since it cannot be monitored continuously but only during the high states of its 35 day precession cycle.

4U $1626-67$ is a 7.66 s pulsar in an ultracompact 42 minute binary. It has $L_X \simeq 10^{37}$ ergs s^{-1} (Chakrabarty 1998). X-ray–timing measurements suggest that we are viewing the bi-

---

[1] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, England, UK; mhvk@ast.cam.ac.uk, jep@ast.cam.ac.uk, ramjw@ast.cam.ac.uk.

[2] Center for Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139; deepto@space.mit.edu.

[3] Isaac Newton Institute for Mathematical Sciences, 20 Clarkson Road, Cambridge CB3 0EH, England, UK.

nary nearly face-on. The less than 0.1 $M_\odot$ mass donor probably fills its Roche lobe. The torque history is reviewed in detail by Chakrabarty et al. (1997a). The pulsar underwent steady spin-up at a mean rate of 0.85 pHz s^{-1} during 1977–1990 and steady spin-down at a mean rate of -0.72 pHz s^{-1} since that time. The 1990 reversal itself was not observed but evidently occurred on a timescale $\lesssim 1$ month. Both the spin-up and the spin-down had a significant quadratic trend.

The X-ray luminosity did not change abruptly at the torque reversal, although there is evidence for a gradual, factor of 2 decay over an interval of 15 yr. However, the long-term (years) 1–20 keV X-ray spectral shape did change, from $dN/dE \propto E^{-1.5}$ during spin-up to $dN/dE \propto E^{-0.4}$ during spin-down (Vaughan & Kitamoto 1997), while the greater than 20 keV spectrum remained unchanged. During spin-up, the pulsar showed strong flares on ∼1000 s timescales, but these flares are absent or much less frequent during spin-down (Chakrabarty et al. 1998).

Quasi-periodic oscillations (QPO) were observed during both spin-up (0.041 Hz; Shinoda et al. 1990) and spin-down (0.048 Hz; Angelini et al. 1995). The detailed sideband structure of the X-ray pulsations and the QPO during spin-down suggests that there is X-ray reprocessing or scattering in material on a prograde orbit, likely at small radius (Kommers, Chakrabarty, & Lewin 1998).

GX 1+4 is a 2 minute pulsar in a wide ($P_{\rm orb} \gtrsim 100$ days) binary with an M giant, and its accretion disk is probably fed by the M giant's wind (Chakrabarty & Roche 1997). Most likely, $L_X \simeq 10^{37}$ ergs s^{-1}, although a larger distance corresponding to $L_X \simeq 10^{38}$ ergs s^{-1} cannot be ruled out. The torque and flux histories are reviewed in detail by Chakrabarty et al. (1997b). The source was bright throughout the 1970s and spinning up rapidly at a mean rate of 6.0 pHz s^{-1}. *EXOSAT* observations in 1983 and 1984 failed to detect it. When detected again at a low luminosity in 1987, it was spinning down at a mean rate of -3.7 pHz s^{-1} (1989–1991). BATSE has observed continued spin-down since 1991, apart from a short spin-up episode and an episode in which the source was not detectable. The torque reversals observed by BATSE were resolved in 5-day–averaged spin measurements.

The long-term mean X-ray luminosity was brighter during the 1970s spin-up interval (and also during the BATSE spin-up event) than during the spin-down intervals in the 1980s and 1990s. However, during the extended spin-down interval observed by BATSE, an anticorrelation between torque and X-ray luminosity was found: increased spin-down for increased X-ray flux. The luminosity during spin-down occasionally flared to values similar to those measured during spin-up in the 1970s. The X-ray spectrum did not change drastically between the 1970s and the late 1980s (Sakao et al. 1990), although considerable variability in the hydrogen column density has been observed.

Centaurus X-3 is a 4.8 s pulsar in a 2.1 day binary with an OB supergiant. It has $L_X \simeq 10^{37}$ ergs s^{-1}. Cen X-3 has shown a long-term spin-up trend of 1.6 pHz s^{-1} since 1972, but BATSE observations resolve this trend into alternating episodes of spin-up and spin-down on 10–100 day timescales (Finger, Wilson, & Fishman 1994). The torque distribution is bimodal, with preferred spin-up/spin-down rates of 7 and -3 pHz s^{-1} (B97). The torque reversals are unresolved in the BATSE measurements and must occur in less than 10 days. Over a factor of 6 range in luminosity, *no* correlation between torque and luminosity is found, and the mean flux is comparable in the two torque states (Vaughan et al. 1998). The spectral shape, pulse profile, and pulsed fraction are correlated with luminosity.

OAO 1657−415 is a 38 s pulsar in a 10.4 day binary with an unidentified companion that is inferred to be an OB supergiant. It has $L_X \simeq 10^{37}$ ergs s^{-1} (Chakrabarty et al. 1993). There is no direct evidence for an accretion disk, but the timing properties of the pulsar strongly suggest disk accretion. Like Cen X-3, the pulsar has shown a long-term spin-up trend since 1979 of ∼1 pHz s^{-1}, but BATSE observations show alternating episodes of spin-up and spin-down on 10–100 day timescales, with typical rates of 7 and -2 pHz s^{-1} (B97). The torque reversals are unresolved in the BATSE measurements. No correlation between torque and luminosity is observed, although this has been tested only over a small range (factor of 2) in luminosity (Koh 1998).

3. WARPED DISKS

Wijers & Pringle (1997, hereafter WP97) have investigated in detail the behavior of irradiated accretion disks in binary stars subject to internal viscous forces, radiation reaction due to illumination from the central source, and the tide from the mass donor. The main aim was to see whether warped disks could form and whether their precession could lead to the superorbital periodicities observed in many X-ray binaries. Here we summarize the results relevant to the torque reversals and compare them with the observations.

Whether the disk becomes unstable to warping depends on the parameter F_*, given by (eq. [18], WP97)

$$F_* = 0.127\eta \frac{\epsilon}{0.1} \frac{1-A}{0.01} \sqrt{\frac{R_{\rm out}}{10^{11}\ {\rm cm}} \frac{1.4\ M_\odot}{M_{\rm NS}}},$$

where η is the ratio of the (R, z) and (R, ϕ) viscosities (see Pringle 1996), $\epsilon \equiv L_X/\dot{M}c^2$ the accretion efficiency, A the disk's X-ray albedo, $M_{\rm NS}$ the neutron star mass, and $R_{\rm out}$ the outer disk radius. WP97 find that for $F_* \lesssim 0.1$, the disks are stable; for $0.1 \lesssim F_* \lesssim 0.15$, the outer parts become warped and precess retrogradely, but the inner parts remain flat; for $0.15 \lesssim F_* \lesssim 0.2$, the inner parts become warped as well, precessing progradely; and for $F_* \gtrsim 0.2$, the disks start to behave somewhat chaotically, precessing less steadily and often having inner parts tilted by more than 90°.

The numerical value of F_* in a real system is quite uncertain, mostly because the disk albedo is poorly known (see WP97), but for typical X-ray binary parameters, one will be close to the unstable regime. We will *assume* that F_* varies, and we will associate the switch between spin-up and spin-down states with a switch between a prograde and a retrograde inner disk (for prograde pulsar rotation). What could drive the variations is unclear, since F_* does not depend directly on quantities such as $\dot{M}$, which are usually thought to vary.

The one parameter that might lead to a switch between two states is the disk albedo. As discussed by WP97, the albedo likely depends on the angle of incidence, with $(1 - A) \lesssim 0.1$ for grazing and $(1 - A) \simeq 0.4$ for normal incidence. One could imagine a situation in which a disk is stable, until a random excursion changes the tilt such that F_* is raised above the critical value, and the disk starts to become warped. This would increase $(1 - A)$ further, leading to further growth, etc. It remains problematic, however, how one would reset the system.

3.1. *Inner-Disk Tilt*

An example of the time evolution of the disk tilt angle for $F_* = 0.2$ is given in Figure 1. It shows that only the inner disk becomes tilted by more than 90° (i.e., retrograde). Reversing the sense of rotation in the inner disk would lead to torque reversals similar to those observed, just as reversing the whole disk would lead to torque reversals in the picture of Nelson et al. (1997). A retrograde inner disk could also lead to the anticorrelation between torque and luminosity observed in the spin-down state of GX 1+4.

In the model in Figure 1, as in most of the simulations we tried, the average inner-disk tilt does not reach 180°. In contrast, for most values of F_* leading to prograde inner disks, the tilts are close to 0°. If this is generally true, then, for a roughly spherical magnetosphere, the spin-change rate in the spin-down state should be systematically lower than that in the spin-up state.[4] For all four sources, the spin-down rate is indeed smaller, by a factor of 1.2–4.

Variations around the mean of about 30° (rms) in the inner-disk tilt angle occur with a characteristic period of ∼4 time units. This corresponds to about 10^5 s in 4U 1626−67, 10^6 s in Cen X-3, 10^7 s in OAO 1657−415, and 10^8 s in GX 1+4. (Note, however, that $F_* = 0.2$ is not necessarily appropriate for all systems.) These variations result in torque fluctuations, which should contribute to the torque noise observed in X-ray pulsars.[5] For Cen X-3 and OAO 1657−415, this may not be very relevant, since the characteristic period is comparable to the duration of a spin-up or spin-down state. However, for 4U 1626−67 and GX 1+4, it is much shorter than the state duration, and we can compare the noise induced by the fluctuations with the observations.

For GX 1+4, the tilt variations correspond to a torque noise power of $\sim 10^{-16}$ Hz^2 s^{-2} Hz^{-1} at 10^{-8} Hz. This is similar to what is observed (B97). For 4U 1626−67, we need to integrate the tilt variations over 10^7 s, the shortest timescale on which the torque noise power has been measured. We find $\sim 10^{-21}$ Hz^2 s^{-2} Hz^{-1}, somewhat larger than the observed $\sim 10^{-22}$ Hz^2 s^{-2} Hz^{-1} at 10^{-7} Hz (Chakrabarty et al. 1997a), but perhaps not inconsistent given the uncertainties in what a real disk would do.

3.2. *Observing through the Disk*

An interesting consequence of associating the spin-down with a flipped-over state is that one should be viewing the neutron star through the disk at least part of the time. We estimate the surface density using a steady, unwarped Shakura-Sunyaev disk. For all four systems, $\dot{M} \simeq 10^{-9}\ M_\odot$ yr^{-1}. The typical radius where the line of sight crosses the disk is where the disk tilt is 90°, about $0.25 R_{\rm out}$ in our simulations. In physical units, this ranges between $\sim 10^{9.5}$ and $\sim 10^{12}$ cm (in 4U 1626−67 and GX 1+4, respectively). With $M_{\rm NS} = 1.4\ M_\odot$ and viscosity parameter α, we find a surface density of $50\alpha^{-4/5}$ and $0.7\alpha^{-4/5}$ g cm^{-2}, respectively (eq. [5.45] of Frank, King, & Raine 1992). This corresponds to column densities $N_{\rm H}$ of about $10^{25}\alpha^{-4/5}$ and $10^{23}\alpha^{-4/5}$ cm^{-2}, respectively. The disk central temperature due to viscous heating is $10^{4.5}\alpha^{-1/5}$ and $10^3\alpha^{-1/5}$ K, respectively, and the ionization parameter $\xi \equiv L_{\rm X}/nR^2$ is a few $\alpha^{7/10}$ (cgs) for both cases. Hence, little ionization is expected, and the disk would be opaque to low-energy X-rays for the dense case.

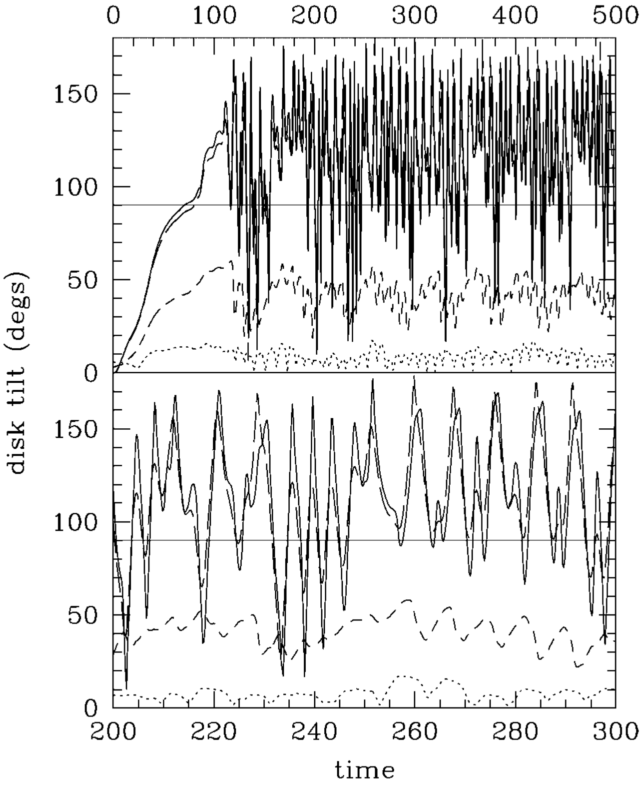

FIG. 1.—Disk tilt as a function of time at various radii. The top panel shows the full simulation, and the bottom panel shows a part of it on an expanded scale. For the simulation, we used $F_* = 0.2$, and matter enters at $\frac{2}{3}$ the outer radius (see WP97). In units of the outer radius, the radii shown are at 0.0083, 0.083, 0.47, and 0.87 (*solid, long-dashed, short-dashed, and dotted lines, respectively*). For 4U 1626−67, Cen X-3, OAO 1657−415, and GX 1+4, the outer radii are approximately 0.18, 2, 5, and 50 × 10^{11} cm, respectively. For $\dot{M} = 10^{-9}\ M_\odot$ yr^{-1}, one unit of time equals 0.3, 5, 17, and 300 days, respectively.

In a twisted disk, the extra viscosity associated with the misalignment between neighboring annuli will lower the column density somewhat. Compared with a similar disk with no irradiation, the column density in the warped disk shown in Figure 1 is lower by a factor of 5 in the outer parts of the disk and by a factor of 2.5 in the inner parts.

Good data on possible spectral changes associated with the torque reversals exist only for 4U 1626−67 (§ 2). The observed decrease and hardening of the 1–20 keV flux in that source may reflect a line of sight through the disk. The spectrum changed mostly below ∼10 keV, suggesting that absorption might play a role. Vaughan & Kitamoto (1997), however, found that the spectrum could not be fitted well by simply increasing the column density $N_{\rm H}$; for an $N_{\rm H}$ sufficient to explain the reduction at close to 10 keV, one would expect no soft X-rays whatsoever.

Increasing $N_{\rm H}$ may not be quite appropriate, since (i) matter in the disk is likely neither cold nor homogeneous; (ii) scattering might be important, as the disk subtends a large solid angle; and (iii) the obscuration will vary will time, because of the precession of the inner disk—for suitable inclinations, the source may even be unobscured part of the time. Of course, given the freedom to change all these, one likely can fit almost

---

[4] We note that changes in the orientation of the neutron star rotation axis due to the nonparallel component of the inner-disk angular momentum are likely small. The effects are reduced by precession for GX 1+4 and 4U 1626−67 and by randomness in inner-disk orientation for Cen X-3 and OAO 1657−415.

[5] The two contributions usually considered are $\dot{M}$ variations and internal torques (see Lamb, Pines, & Shaham 1978).

anything. Vaughan & Kitamoto could fit the 4U 1626−67 spectrum assuming partial covering, where 86% of the source is obscured with $N_{\rm H} = 10^{23.8}$ cm^{-2} and the remainder unobscured. If this were the correct model, it might reflect either spatial or temporal covering (the spectrum was a long-term average).

3.3. *Problems*

There are several difficulties in applying the warped disk model to the torque reversal observations in detail. The primary one concerns the timescales between the reversals. In those simulations where a retrograde inner disk arose, its mean inclination remained relatively stable (and >90°) after its initial growth, with only short excursions to prograde flow. This is at odds with the observations, which show roughly equal times in spin-up and spin-down.

Furthermore, each of the four systems considered has an aspect that is not easily explained in the retrograde disk picture. In 4U 1626−67, there is QPO evidence for prograde motion during spin-down, likely at a small radius (§ 2). In GX 1+4, the torque reversals observed by BATSE were clearly accompanied by luminosity changes. Finally, in both high-mass X-ray binaries (Cen X-3 and OAO 1657−415), the lack of a clear correlation between spin-change rate and luminosity (in both spin-up and spin-down states) seems to confound all the existing models.

A number of potentially important effects have been neglected in the WP97 simulations. These include the dependence of the albedo on the angle of incidence (and the resulting variations of F_*), the increased disk scale height and thus reduced density due to irradiation (resulting in larger ξ and possibly different disk opacity), and the varying "splash point" where the accretion stream—which is in the orbital plane—hits the precessing disk (resulting, e.g., in inward advection in addition to viscosity). Accounting for these properly may change considerably the detailed predictions for warped disks. However, the existence of warps and transitions to retrograde flow under certain conditions seems a general feature.

4. CONCLUSIONS

It has been suggested previously that retrograde disk flows would be an elegant explanation for torque reversals in disk-fed X-ray pulsars. It has been an open question, however, as to how such a flow would be created when mass is transferred by Roche lobe overflow and thus enters the accretion disk in a prograde orbit. We have pointed out that strong disk warping may produce a retrograde flow close to an accreting neutron star from an initially prograde flow in the outer disk.

While this simple picture allows us to understand some of the characteristics of the observations, it does not match all of them. This could reflect the neglect in the models of many potentially important effects. Our main point here, however, is that quasi-stable retrograde disk flows are physically plausible and that they may thus be (part of) what causes the spin-down states in persistent disk-fed X-ray pulsars.

Despite the uncertainties in the models, it remains true generally that if the spin-down state is due to a flipped-over inner disk, it should be associated with enhanced absorption. One would expect relatively strong absorption edges, especially of iron, which could be looked for with high-resolution spectroscopy. The absorption should vary with time as the inner disk precesses (although the precession is not necessarily very coherent). With more disk surface exposed to the central X-ray source, we also would expect increased scattering and stronger fluorescence lines.

We thank Mark Finger and Dimitrios Psaltis for useful discussions. D. C. acknowledges support from a NASA *Compton GRO* fellowship and R. A. M. J. W. from a Royal Society URF grant.

REFERENCES

Angelini, L., White, N. E., Nagase, F., Kallman, T. R., Yoshida, A., Takeshima, T., Becker, C. M., & Paerels, F. 1995, ApJ, 449, L41

Bildsten, L., et al. 1997, ApJS, 113, 367 (B97)

Chakrabarty, D. 1998, ApJ, 492, 342

Chakrabarty, D., & Roche, P. 1997, ApJ, 489, 254

Chakrabarty, D., et al. 1993, ApJ, 403, L33

———. 1997a, ApJ, 474, 414

———. 1997b, ApJ, 481, L101

———. 1998, in preparation

Finger, M. H., Wilson, R. B., & Fishman G. J. 1994, in Second Compton Symp., ed. C. E. Fichtel, N. Gehrels, & J. P. Norris (New York: AIP), 304

Frank, J., King, A. R., & Raine, D. J. 1992, Accretion Power in Astrophysics (Cambridge: Cambridge Univ. Press)

Ghosh, P., & Lamb, F. K. 1979, ApJ, 234, 296

Koh, D. 1998, Ph.D. thesis, Caltech

Kommers, J. M., Chakrabarty, D., & Lewin, W. H. G. 1998, ApJ, 497, L33

Lamb, F. K., Pines, D., & Shaham, J. 1978, ApJ, 224, 969

Makishima, K., et al. 1988, Nature, 333, 746

Nelson, R. W., et al. 1997, ApJ, 488, L117

Pringle, J. E. 1996, MNRAS, 281, 857

———. 1997, MNRAS, 292, 136

Sakao, T., et al. 1990, MNRAS, 246, L11

Shinoda, K., Kii, T., Mitsuda, K., Nagase, F., Taaka, Y., Makishima, K., & Shibazaki, N. 1990, PASJ, 42, L27

Vaughan, B. A., Chakrabarty, D., Favata, M., Finger, M. H., Nelson, R. W., & Prince, T. A. 1998, in preparation

Vaughan, B. A., & Kitamoto, S. 1997, ApJ, submitted (astro-ph/9707105)

Wijers, R. A. M. J., & Pringle, J. E. 1997, MNRAS, submitted (WP97)

Yi, I., Wheeler, C., & Vishniac, E. T. 1997, ApJ, 481, L51