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A Super-Eddington Wind Model for GRO J1655-40

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Abstract. A model for GRO J1655-40 is described in which the hard X/γ-ray behavior, and long delay between the X/γ and radio outbursts, are explained by processes which occur when the accretion rate approaches and exceeds the Eddington limit. The principal feature of the model is a dense, optically thick, super-Eddington wind ejected from the center of the accretion disk. The wind is responsible for determining the luminosity and spectral evolution of the object and for suppressing the formation of a fast, relativistic jet while the accretion rate is above the Eddington limit.

Our model makes use of the "magnetic switch" mechanism we recently discovered with MHD simulations of jet production in magnetized accretion disk coronae. A fast jet can be turned on (or off) by increasing (or decreasing) the Alfvén velocity in the corona relative to a critical value. Examination of models of sub- and super-Eddington disks shows that V_A remains below the critical value while the wind is present, but could exceed it when the wind disappears and a hot, optically thin corona forms.

1. Introduction

GRO J1655-40 is one of two galactic X/γ-ray sources that eject radio jets exhibiting superluminal motion. In this paper we deal mainly with the first detected hard X/γ-ray outburst in the source, which began on 28 July, 1994 and ended on 16 August (Harmon *et al.* 1995). For ~16 days after the initial X/γ rise, the object remained radio weak, until a strong radio outburst began on ~13 August (Campbell-Wilson & Hunstead 1994). VLA and VLBI observations of the source (Tingay et al. 1995; Hjellming & Rupen 1995) showed a relativistically-expanding jet ($\Gamma \sim 2.5$) which, when extrapolated back in time, appeared to have zero separation on the date of the initial rise in radio flux.

Several peculiar features of the object are noteworthy. Firstly, the X/γ-ray luminosity was unusually high — at least $L(0.1 - 500keV) \sim 10^{38} ergs^{-1}$ — which is the Eddington luminosity for a solar mass (Harmon *et al.* 1995). Secondly, the X/γ spectrum exhibited unusual behavior, softening at outburst, then slowly hardening, then softening when the luminosity dropped on 8 August, and finally suddenly hardening again at the onset of the radio outburst (Wilson *et al.* 1994; Harmon 1995). Thirdly, the delay between the onset of the X/γ outburst and radio outburst is enormously long for this system — 10^{10} dynamical times for an accretion disk around a neutron star or black hole. While the radio outburst is clearly related to the X/γ-ray outburst, the onset of the jet must have signaled a *secular change* in the state of the accreting system, rather than a dynamical response to the original accretion event.

We suggest that GRO J1655-40 underwent a super-critical, or "super-Eddington", accretion event, such that $\dot{M} > \dot{M}_{Edd} \approx 2 \times 10^{18}\,\mathrm{g\,s^{-1}}(M/M_\odot)$. Such an event explains the high luminosity and strange spectral evolution. We also identify the delay in the onset of the radio outburst as the *suppression of jet formation* during the high luminosity phase. Most of the details of this model are discussed in Meier (1996); here we review the model and relate it to recent work performed by our group on jet formation models.

2. The Super-Eddington Model

For a super-Eddington accreting object, the disk will be geometrically thick with height $H \sim R$ for $R < r_{trap} \equiv (\dot{M}/\dot{M}_{Edd})R_{in}$ (Shakura & Sunyaev 1973; Meier 1982), where R_{in} is the inner (cylindrical) radius of the disk and r_{trap} is the "trapping radius", interior to which the advection of photons by accretion and convection dominates diffusion. Because of the highly convective nature of the region interior to r_{trap} (Begelman & Meier 1982), much of the energy generated ($\epsilon \dot{M} c^2 > L_{Edd}$) is not advected into the black hole (or neutron star) but rather is released at the thick disk surface. In a steady state this release drives a strong, dense wind that carries off the energy generated in excess of the Eddington limit: $L_{wind} = \epsilon_{eff} \dot{M}_{acc} c^2 - L_{Edd}$, where $\dot{M}_{acc} \equiv \dot{M} - \dot{M}_{wind}$ is the amount of matter finally accreting onto the compact object, and ϵ_{eff} is an effective efficiency.

The bolometric photon luminosity of the disk-wind system remains at $\sim L_{Edd}$. The behavior of the spectral hardness is opposite to that normally associated with sub-Eddington (normal) accretion disks: as $\dot{M}$ decreases, T *increases* as the wind becomes more optically thin. The observed luminosity and spectral evolution can be fit reasonably well with a sudden increase of the accretion rate to $\dot{M}/\dot{M}_{Edd} \sim 3$ on 28 July and then a roughly linear decrease to zero thereafter. The predicted radiation temperature drops to $\sim$100 keV as the wind forms, then hardens to $\sim$500 keV as the wind mass loss rate $\dot{M}_{wind}$ decreases with decreasing $\dot{M}$, and finally softens again when $\dot{M}/\dot{M}_{Edd} < 1$ and the disk becomes geometrically thin and cool. Only the sudden hardening after 13 August is not explained by standard disk models; we attribute this behavior to the appearance of a hot, tenuous, optically thin corona. Below we discuss why such a corona is necessary for the formation of a fast jet.

3. Jet Formation Simulations

To treat the formation (and suppression) of jets in the GRO J1655-40 system, we appeal to one of the more promising models of jet production — the Blandford-Payne MHD process in the coronae of thin accretion disks (Blandford & Payne 1982). In our version of this model a poloidal magnetic field is anchored in a dense, cool ($T \sim 10^{7-8}$K) disk and threads a hot ($T \gtrsim 10^9$K) corona. Centrifugal action of the field on the coronal material, plus the coiling of the field around the rotation axis by differential rotation, serve to accelerate and collimate the material into a jet. Note that, if the magnetic field strength is of the same order as that providing the accretion disk viscosity, then magnetic forces do not disrupt (or accelerate) much of the disk since

$$V_{A,disk} \equiv \frac{B}{(4\pi\rho_{disk})^{1/2}} \sim \alpha^{1/2}\frac{H}{R}V_{esc} << V_{esc} \tag{1}$$

where $V_{A,disk}$ and V_{esc} are the local Alfvén and escape velocities, respectively, in the disk. However, there exists a critical *coronal* density $\rho_{crit} \equiv \alpha H^2 \rho_{disk}/R^2$, such that if $\rho_{corona} < \rho_{crit}$, then $V_{A,corona} > V_{esc}$.

In recent work, reported elsewhere (Meier *et al.* 1996), we have performed over 40 magnetohydrodynamic disk corona simulations using a "2.5-dimensional" code running on the Caltech/JPL parallel supercomputers. While non-relativistic, these simulations can be used to infer the results of a truly relativistic code, provided the thermal and magnetic inertia terms remain small compared to ρc^2 and one identifies the velocity with the spatial component of the 4-velocity ($\Gamma \mathbf{V}$). These authors find that jets are produced for a wide range of magnetic field geometries, and that the jet character is a strong function of the initial strength of the Alfvén velocity in the corona: for low values ($V_A < V_{esc}$ [weak field, dense corona]) the resulting jet velocities are relatively slow ($V_{jet} \sim V_A$), but for moderate values ($V_A > V_{esc}$ [strong field, tenuous corona]) the jet velocities are *1-2 orders of magnitude higher* ($V_{jet} >> V_A > V_{esc}$). The process appears to contain a "magnetic switch" which produces very fast, and presumably relativistic, jets when the ratio of magnetic energy to gravitational binding energy in the corona is greater than unity.

4. Jet Suppression

In Meier (1996) it was suggested that the jet in GRO J1655-40 could be suppressed for $\dot{M} \gtrsim \dot{M}_{Edd}$ by the expected Papaloizou & Pringle (1984) instabilities that should destroy the geometrically thick disk. However, in light of the above MHD simulations, appealing to complete destruction of the inner disk by P-P instabilities in order to suppress the jet is neither necessary, nor desirable, and may not occur anyway in realistic accretion situations (Hawley 1991). Instead, all that is needed to suppress a fast jet is a particularly dense (or non-existent) corona, as would be the case when the disk is ejecting a dense, optically thick, super-Eddington wind. Indeed, we find from wind models (Meier 1982) and disk models (Shakura & Sunyaev 1973) that $\rho_{wind}/\rho_{crit} > \alpha^{-1} > 1$. Therefore, a fast jet should not form when the wind is present, and the speed of any resulting slow jet could be quite low ($\sim \alpha^{1/2}V_{esc}$) if α were small. In our model, then, the super-Eddington phase produces a weak radio source (and jet) because the wind material is too heavy to be accelerated to escape velocity. Only when $\dot{M} < \dot{M}_{Edd}$ does the wind subside, the disk become geometrically thin, and a hot (continuously-replenished) corona develop, which *is* light enough to be accelerated to high speeds.

5. Discussion

The main difficulty of the super-Eddington model for GRO J1655-40 is that the observed bolometric luminosity is somewhat lower than predicted. The derived mass of the compact object of $\gtrsim 3M_\odot$ (Bailyn *et al.* 1995) implies that the $0.1 - 500keV$ luminosity should have been closer to three times what is observed. One possible explanation, which is consistent with the eclipses seen in the binary system, is that the actual X/γ-ray source is hidden by a nearly edge-on flared disk, and we see only a fraction of the X/γ-rays in reflection from the disk back side, with the rest of it beamed loosely away from the line of sight. If this scenario is correct, then GRO J1655-40 and GRS 1915+105 (the other galactic superluminal source; Mirabel & Rodriguez 1994) would be virtually identical objects. Both would have masses of a few $M_\odot$, both would have produced $\Gamma \sim 2$ jets, and both would have been super-Eddington X/γ-ray sources, reaching luminosities of $\sim 3 - 4 \times 10^{38} ergs^{-1}$.

It should be emphasized that our model deals with only the short-term evolution of the source and not the long-term decline in the strength of the radio outbursts that occurred over a period of months while the X/γ-ray outburst luminosity remained roughly the same (Hjellming & Rupen 1995). Models explaining how this source could evolve from a radio loud mini-quasar to a radio quiet one may have to invoke some more fundamental property of the accreting system, such as the angular momentum or electric charge of the black hole itself.

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Discussion

J. LI: How sensitively do the simulated jets depend on the disc boundary condition (e.g. prescribed Keplerian rotation)?

D. Meier: Some of that sensitivity was discussed in the presentation (sensitivity to magnetic field strength; insensitivity to field orientation). We have not investigated different rotation laws yet. One boundary condition, to which the Type I jets might be sensitive, is the inner corner at $r = z = 0$. Ours is reflective, not inflow (as in the case of a blackhole). There is a small chance the Type I (filled) jets might be weakened or disappear if an inflow corner condition were implemented.

U. Torkelsson: In turbulence simulations the magnetic field is dominated by its toroidal component. How does it affect the jet?

D. Meier: We have performed some simulations with a dominant magnetic field, but have not done a full parameter study, so my answer will be somewhat tentative. At present, it appears that a large toroidal component enhances the mass loss rate in the jet, increasing the speed of the bow shock but not necessarily the flow velocity of the jet material itself. That is, the jets become heavier.