ACCRETION FROM STELLAR WINDS

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ABSTRACT. Recent calculations have demonstrated that accretion from a stellar wind is very probably unsteady. The average rate of accretion of angular momentum is lower by about a factor 5 than the rate at which angular momentum is deposited into the Bondi-Hoyle accretion cylinder. This makes disk formation from wind accretion very difficult, in particular in the case of massive x-ray binaries. A combination of x-ray, uv and optical observations of symbiotic and related systems, as well as spin-up information on x-ray binaries, can be used to determine whether an accretion disk does form. Such observations can provide us with valuable information on the process of accretion from an inhomogeneous medium.

1. INTRODUCTION

The problem of accretion from an infinite medium by a gravitating object, is important for neutron stars accreting from stellar winds of early type companions, white dwarfs and main sequence stars accreting from winds of cool giants and galaxies moving in the intergalactic medium.

In the original Hoyle and Lyttleton (1939) picture, particles in the medium were assumed to follow their free Keplerian paths far from the accreting object, and interact inelastically only on the downstream axis. This interaction was assumed to lead to a complete cancellation of transverse (to the accretion line) momentum, leaving the momentum component parallel to the accretion line unchanged. Based on the Hoyle-Lyttleton assumption, it is possible to calculate the maximal impact parameter (the "accretion radius") for which, following the interaction, the matter will have a velocity lower than the escape velocity. All the material entering a cylinder with a radius equal to the accretion radius R_A, was therefore assumed to be accreted, giving an accretion rate

$$\dot{M}_{HL} = \pi R_A^2 \rho_\infty V = \frac{4\pi (GM)^2 \rho_\infty}{V^3} \quad , \qquad (1)$$

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where M is the mass of the accreting object, ρ_∞ and V are the density and velocity of the gas at infinity. Bondi and Hoyle (1944) replaced the unphysical, infinite density, accretion line in the Hoyle-Lyttleton picture by a finite density accretion cone. They found an accretion rate (still for a velocity dominated flow) of

$$\dot{M}_{BH} = \frac{4\pi\ \alpha(GM)^2 \rho_\infty}{V^3} \tag{2}$$

where $\frac{1}{2} \lesssim \alpha \lesssim 1$ is a parameter that is indeterminate by the theory (dependent on initial conditions). A different limiting case has been treated by Bondi (1952) who considered the problem of spherical accretion from a stationary medium onto a gravitating object. He found for this (pressure dominated) case an accretion rate of

$$\dot{M}_B = 4\pi\ \lambda(\gamma) R_B^2\ \rho_\infty\ C_\infty = \frac{4\pi\ \lambda(\gamma)\ (GM)^2 \rho_\infty}{C_\infty^3} \tag{3}$$

where C_∞ is the speed of sound (at infinity) and $\lambda(\gamma)$ is a parameter (depending on the specific heat ratio) assuming values in the range 0.25 - 1.12. Combining the two limiting cases represented by eqs. (2) and (3), an interpolation formula for the accretion rate can be written as (Bondi 1952)

$$\dot{M}_B \simeq \frac{4\pi\ (GM)^2 \rho_\infty}{(V^2 + C_\infty^2)^{3/2}} \tag{4}$$

The problem of accretion from an infinite medium has gained renewed interest, in particular with the realization of its relevance to compact objects accreting from stellar winds and to common envelope evolution. Much of the more recent work has concentrated on the use of multi-dimensional numerical hydrodynamics (e.g. Hunt 1971, 1975, 1979, Livio, Shara and Shaviv 1979, Okuda 1983, Shima et al. 1985). The results obtained in these calculations were generally consistent with the Bondi-Hoyle theory, as expressed by eq. 4. The most recent fluid dynamical calculations were performed by Shima et al. (1985) who used a two dimensional, second-order accurate, Osher scheme (e.g. Chakravarthy and Osher 1983). A pseudo-particle description of the hydrodynamics was used by Livio et al. (1986a, b) and by de Kool and Savonije (1987). The results of these works show that the accretion rate (in the homogeneous case) can be expressed as

$$\dot{M} = F(\gamma,\mu) \cdot \frac{4\pi\ (GM)^2 \rho}{V^3} \tag{5}$$

with average values of $F(\gamma,\mu)$ of order 0.75 for $\gamma = 5/3$ and 1.0 for $\gamma \lesssim 4/3$ (μ is the Mach number).

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2. ACCRETION FROM STELLAR WINDS - ACCRETION OF ANGULAR MOMENTUM

The basic problem associated with accretion from a stellar wind is the fact that the medium can no longer be considered homogeneous. Indeed, if the accretion cylinder remains unchanged, then due to the fact that there exists a gradient in the density (and possibly the velocity) of the stellar wind, material entering on one side of the accretion cylinder is denser (and may have a different velocity) than on the other side. This of course leads to a net deposition of angular momentum into the symmetric (about the accreting object) Bondi-Hoyle cylinder. As a consequence of the lack of a basic theory for the inhomogeneous case (despite some early attempts by Gethig (1951) and Dodd and McCrea (1952)), it has been assumed by a number of authors (e.g. Illarionov and Sunyaev 1975; Shapiro and Lightman 1976, Wang 1981) that all the angular momentum deposited into the symmetric cylinder is actually accreted. This leads to a rate of accretion of angular momentum of

$$\dot{L}_{BH} = \frac{1}{2} \eta R_A^2 \Omega_{orb} \dot{M} \quad (6)$$

where η is a parameter of order unity, detailed expressions for which (in terms of the radial and azimuthal density and velocity gradients) were obtained by Wang (1981).

The first to note that eq. (6) may significantly overestimate the rate of accretion of angular momentum were Davies and Pringle (1980). They pointed out that in the context of the original Hoyle-Lyttleton picture, in order to get accreted, particles from both sides of the accreting object have to cancel their momentum component transverse to the accretion line. They suggested therefore, that a similar situation should occur in the inhomogeneous case, with the accretion line somewhat displaced towards the lower density side. This should of course result in no accretion of angular momentum. Davies and Pringle admitted that their highly simplified, two dimensional treatment may not be valid in the real case which requires a fully three-dimensional calculation.

The first (and to date the only) three dimensional numerical calculations of accretion from a medium containing a density gradient, were performed by Livio et al. (1986a, b) and Soker et al. (1986). They found that when pressure effects were neglected (corresponding to a hypersonic flow), the accretion cylinder (representing the material that was eventually accreted), was displaced towards the lower density side in such a way that a displaced accretion cone formed (Fig. 1). The average rate of accretion of angular momentum was found to be only about 8% of that represented by eq. (6) (with $\eta = 1$). The calculations were then extended to include pressure effects, first in the isothermal case (Soker et al. 1986) and then for different values of the specific heat ratio γ. All cases resulted in a displacement of the accretion cylinder (and a corresponding one of the accretion cone, e.g. Fig. 2 for the isothermal case). The average rate of accretion of angular momentum, never exceeded ~ 23% of the rate at which angular momentum was deposited into the Bondi-

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Hoyle symmetric accretion cylinder (represented by eq. (6)). Very similar results were obtained by Anzer, Börner and Monaghan (1987), who performed, however, a two dimensional calculation (which does not represent accurately the real flow in the inhomogeneous case).

The following important point should be emphasized. Due to the relatively coarse grid (imposed by memory limitations) in a three dimensional calculation, the values quoted above for the rate of accretion of angular momentum are average values only. Also, the 3D calculations could not resolve the flow structure over small scales (in particular, the scale of the density gradient was always chosen to be lrger than the accretion radius). When the finest possible grid (allowed on the CRAY X-MP/48 supercomputer) has been used (Livio and Soker 1986), no steady state was found. A similar result was obtained in the two dimensional calculations of Matsuda, Inoue and Sawada (1987) and of Fryxell and Taam (1987) who found the flow pattern to change its structure, from a displaced cone to a disk. The disk itself was found to reverse its rotational direction on a dynamical timescale. It should be noted however, that these fluctuations in the flow pattern are very probably enhanced in a two dimensional calculation, which does not allow the extra smoothing that a flow in the third dimension can provide. If the variations found by Matsuda et al. (1987) are real, then they should lead to oscillations in both the mass accretion rate and (to an even larger extent) the angular momentum accretion rate (which can even change sign).

3. GENERAL IMPLICATIONS FOR SYMBIOTIC SYSTEMS, X-RAY BINARIES AND RELATED OBJECTS

The determination of spectral types and luminosity classes for the cool components of a number of symbiotic systems (Kenyon and Fernandez-Castro 1987), as well as the determination of orbital periods from radial-velocity variations in the primary (Garcia 1986), suggest a division into semi-detached systems and detached systems. The detached systems include AG Dra ($P \simeq 554$ days, Meinunger 1981), AG Peg ($P \simeq 830$ days Hutchings et al. 1975), SY Mus ($P \simeq 627$ days Kenyon et al. 1985), Mira variable systems such as R Aqr and V1016 Cyg and possibly V1329 Cyg ($P \simeq 950$ days, Taranova and Yudin 1986), EG And ($P \simeq 470$ days, Oliversen et al. 1985) BX Mon, BF Cyg, TX CVn and HM Sge (Garcia 1986 and references therein). In the detached systems, the hot component must accrete mass from the giant's stellar wind. The total accretion luminosity that is obtained, based on the results presented in Section 1, is

$$L_{acc} = \frac{GM_{WD}\dot{M}_{acc}}{R_{WD}} = 4.0 \times 10^{36} \left[\frac{F(\gamma,\mu)}{0.9}\right] \left(\frac{M_{WD}}{M_{WD}+M_G}\right)^{2/3} \left(\frac{M_{WD}}{M_\odot}\right)^{2/3} \left(\frac{R_{WD}}{6\times10^8\,\mathrm{cm}}\right)^{-1}$$

$$\left(\frac{V_W}{2\times10^6\,\mathrm{cm/s}}\right)^{-1} \left(\frac{V_{rel}}{5\times10^6\,\mathrm{cm/s}}\right)^{-3} \left(\frac{P_{orb}}{1\,\mathrm{yr}}\right)^{-4/3} \left(\frac{\dot{M}_W}{10^{-6}M_\odot/\mathrm{yr}}\right) \mathrm{erg\ s^{-1}} \qquad (7)$$

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where M_{WD} and R_{WD} are the mass and radius of the accreting component (presumably a white dwarf), P_{orb} is the orbital period, V_W is the wind velocity, $\dot{M}_W$ is the rate of mass loss from the giant and V_{rel} is the relative velocity between the white dwarf and the wind $V_{rel} = (V^2_{orb} + V^2_W)^{1/2}$.

If an accretion disk does not form (see below), then as the accreted matter flows radially onto the white dwarf, a strong standoff shock forms, at a distance above the star, allowing the post-shock material to cool. If the dominant cooling mechanism is Bremsstrahlung, then the distance of the shock from the stellar surface is roughly (e.g. Hoshi 1973, Aizu 1973, Fabian, Pringle, and Rees 1976)

$$d = \frac{L_{acc}}{f \cdot 4\pi R^2_{WD}\, \epsilon_{ff}} \simeq 2.6 \times 10^8\, f \left(\frac{\dot{M}_{acc}}{10^{19}\,gs^{-1}}\right)^{-1} \left(\frac{M_{WD}}{M_\odot}\right)^{3/2} \left(\frac{R_{WD}}{6x10^8\,cm}\right)^{1/2} cm \qquad (8)$$

where f is the fraction of the white dwarf's surface over which accretion takes place. The x-ray and uv luminosity produced by the accretion is characterized (for non magnetic white dwarfs) by three components (e.g. Lamb 1983): (1) A hard x-ray component, resulting from bremsstrahlung emission is the post-shock region, with a characteristic shock temperature

$$T_s = \frac{3}{8}\frac{GM_{WD}\, m_p\, \mu_m}{kR_{WD}} \simeq 6.2 \times 10^8 \left(\frac{M_{WD}}{M_\odot}\right)\left(\frac{\mu_m}{0.615}\right)\left(\frac{R_{WD}}{6x10^8\,cm}\right)^{-1} K \qquad (9)$$

where μ_m is the mean molecular weight, m_p is the proton mass and k is Boltzmann's constant. The maximal luminosity in this component is about one half of the accretion luminosity (eq. 7). (2) A soft x-ray blackbody component, produced by bremsstrahlung radiation emitted towards the white dwarf, absorbed, and re-radiated from the star's surface. The characteristic temperature of this component is

$$T_{bb} = \left(\frac{L_{acc}}{f \cdot 4\pi R^2_{WD}\sigma}\right)^{1/4} = 3 \times 10^5\, f^{-1/4}\left(\frac{\dot{M}_{acc}}{10^{19}\,gs^{-1}}\right)^{1/4}\left(\frac{M_{WD}}{M_\odot}\right)^{1/4}\left(\frac{R_{WD}}{6x10^8\,cm}\right)^{-3/4} k. \qquad (10)$$

Detailed calculations (e.g. Kylafis and Lamb 1982) show that this soft x-ray component is always present in non magnetic white dwarfs. (3) Secondary radiation from Compton heated pre-shock material. If the white dwarf is magnetized, a fourth, uv cyclotron component is produced in the hot emission region and component (2) above is partly produced by cyclotron photons. In general the relative strength of the different components depends sensitively on the accretion rate and on the magnetic field strength (e.g. Lamb and Masters 1979). In particular, white dwarfs with fields of the order of 10^7 gauss or more should appear as intense uv sources with an x-ray luminosity (and optical luminosity) amounting to not more than a few percent of

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L_{acc}. Another process that can have a significant effect on the observed spectrum is steady nuclear burning on the white dwarf surface. The energy produced by nuclear burning results in a blackbody flux of soft x-rays, which is capable of cooling the hard x-ray emission region by inverse Compton scattering. This results in a reduction in the hard x-ray luminosity by about an order of magnitude (Weast et al. 1981).

The situation can be quite different if accretion is mediated by an accretion disk. In this case, half of the accretion energy is radiated as black body radiation from the disk. In the context of standard, steady state, optically thick disks, this produces a $\nu^{1/3}$ power law spectrum in the optical and uv (e.g. Shakara and Sunyaev 1973, Pringle 1981). The other half of the accretion energy is emitted in the boundary layer between the disk and the white dwarf. The boundary layer can emit soft x-rays (as a black body if optically thick, Pringle 1977) and perhaps hard x-rays (by shocks or turbulent viscosity, Pringle and Savonije 1979, Tylenda 1981) if optically thin. Unfortunately, the exact processes occurring within the boundary layer are still unknown (see e.g. Livio and Truran 1987), but many cataclysmic variables have been identified as x-ray sources (mostly showing a hard component, e.g. Cordova and Mason 1983).

The differences between radial and disk accretion, coupled with the fact that in many symbiotic systems, accretion takes place via a stellar wind, demonstrate the importance of being able to determine whether disks can form from wind accretion. Furthermore, in massive x-ray binaries (in which neutron stars accrete from winds of early type companions), the question of accretion of angular momentum has direct consequences for the spin-up of neutron stars.

In the case of a non magnetic white dwarf accreting from a stellar wind, an accretion disk can form, if the specific angular momentum of the accreted matter is sufficient to allow it to enter a Keplerian orbit around the white dwarf. This can be expressed by the condition

$$\ell_{acc} > (GM_{WD} R_{WD})^{1/2} , \qquad (11)$$

where ℓ_{acc} is the specific angular momentum of the material captured from the wind. Using the results presented in Section 2 for the average rate of accretion of angular momentum, eq. (11) translates into the following condition for the formation of a (quasi steady) accretion disk

$$V_{rel} \lesssim 8.4 \times 10^6 \left(\frac{\zeta\eta}{0.2}\right)^{1/4} \left(\frac{P_{orb}}{1\ \mathrm{yr}}\right)^{-1/4} \left(\frac{M_{WD}}{M_\odot}\right)^{3/8} \left(\frac{R_{WD}}{6\times10^8\ \mathrm{cm}}\right)^{-1/8} \mathrm{cm\ s^{-1}} \qquad (12)$$

where η is the factor appearing in eq. 6 and ζ represents the average fraction of the angular momentum deposited into the symmetric accretion cylinder that is actually accreted (according to the 3D calculations). The value of ζ was found to be of order 0.1 in the isothermal case and of order 0.2-0.25 for γ in the range 4/3 to 5/3.

If the accreting object is magnetized, as is often the case for the neutron stars in massive x-ray binaries, then for a disk to form, its radius must be larger than the magnetospheric radius. This results in the condition (where values appropriate for x-ray binaries were used)

$$V_{rel} \lesssim 4.0 \times 10^7 \left(\frac{\zeta\eta}{0.2}\right)^{1/4} \mu_{30}^{-1/4} \left(\frac{M_x}{M_\odot}\right)^{5/14} \left(\frac{P_{orb}}{1\mathrm{day}}\right)^{-1/4} \left(\frac{R_x}{10^6\mathrm{cm}}\right)^{1/28}$$

$$\times \left(\frac{L_x}{10^{37}\mathrm{ergs}^{-1}}\right)^{1/28} \mathrm{cm\ s^{-1}} \qquad (13)$$

where μ_{30} is the neutron star's magnetic moment (in 10^{30} gauss cm^3). An additional piece of information in the binary x-ray sources case is provided by observations of spin-up of the neutron star. Equating the average rate of accretion of angular momentum to the one implied by the observed spin-up, gives

$$\dot{L}_{acc} = \left|\frac{\dot{P}}{P_s}\right|_{obs} \left(\frac{2\pi}{P_s}\right) I_x \quad , \qquad (14)$$

where P_s is the spin period of the neutron star and I_x its moment of inertia. This provides another constraint on the relative velocity

$$V_{rel} = 8.9 \times 10^7 \left(\frac{\zeta\eta}{0.2}\right)^{1/4} \left(\frac{|\dot{P}/P_s|}{10^{-11}\mathrm{ss}^{-1}}\right)^{-1/4} \left(\frac{L_x}{10^{37}\mathrm{ergs}^{-1}}\right)^{1/4} \left(\frac{M_x}{M_\odot}\right)^{1/4}$$

$$\times \left(\frac{P_{orb}}{1\mathrm{d}}\right)^{-1/4} \left(\frac{R_x}{10^6\mathrm{cm}}\right)^{1/4} \left(\frac{I_x}{10^{45}\mathrm{gcm}^2}\right)^{-1/4} \left(\frac{P_s}{100\mathrm{s}}\right)^{1/4} \mathrm{cm\ s^{-1}} \qquad (15)$$

We are now in the position to apply these results to a few specific systems.

4. DISCUSSION OF SOME INDIVIDUAL SYSTEMS

We shall now use the general results of the preceding sections, for some symbiotic and related systems.

AG Dra

The orbital period of this system is P_{orb} = 554 days (Meinunger 1979, Oliversen and Anderson 1982, Garcia 1986). If we adopt $M_G \simeq 1.5\ M_\odot$, $M_{WD} \simeq M_\odot$, and a wind velocity $V_W \simeq 100$ km/sec (Garcia 1986), then from eq. (7) we obtain an accretion luminosity of

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$$L_{acc} \simeq 2.6 \times 10^{32} \left(\frac{\dot{M}_W}{10^{-8} M_\odot/yr}\right) \text{ erg s}^{-1} . \qquad (16)$$

AG Dra has been detected as a soft x-ray source with a luminosity of $L_x = 2 \times 10^{32}$ erg s^{-1} (Anderson, Cassinelli, and Sanders 1981). For a (quasi steady) disk to form, the relative velocity between the white dwarf and the wind must satisfy $V_{rel} \lesssim 7.6 \times 10^6$ cm, implying $V_W \lesssim 67$ km s^{-1}. This is lower than the value we have used, $V_W \sim 100$ km s^{-1}, but in view of the uncertainties in both the observations and the theoretical predictions, a wind fed disk can probably form in this system. It should be noted that once a disk starts to form, it can spread by viscous transport of angular momentum. The absence of a harder x-ray component is somewhat puzzling since at the relatively low accretion rates implied for this system (for any reasonable wind mass loss rate, $\dot{M}_W \lesssim 10^{-7}$ $M_\odot$/yr), a hard component would perhaps be expected both for radial and disk accretion. However, since the source of the hard x-ray emission in cataclysmic variables is not really entirely clear, the absence of hard x-rays favors probably the existence of a disk.

Mira A + B

While the Mira AB system itself can be considered only "mildly" symbiotic (e.g. Whitelock 1987), it is closely related to symbiotic systems which contain Mira variables (e.g. R Aqr and V1016 Cyg). Mira B is thought to be a white dwarf accreting from the wind of Mira A (Warner 1972, Livio and Warner 1984). The situation here is somewhat complicated by the fact that no reliable orbital period is known. Fernie and Brooker (1961) considered 261 yr as the most plausible of their possible solutions, which included 59 and 169 years. Hopmann (1969) found 139 and 842 years. Baize (1980) found 400 years, but Walker (1985) concluded that all the existing orbits are bad. We shall use $P_{orb} = 400$ yrs, this being close to the average of all the existing periods. While the distance of 77 pc (Jenkins 1952) is often quoted, this has been recently questioned by Whitelock (1987), who uses d = 120 pc. If we still use the former value, a wind velocity of $V_W = 5.6 \times 10^5$ cm s^{-1} (Wannier et al. 1980) and a wind mass loss rate of $\dot{M}_W \simeq 10^{-7}$ $M_\odot$/yr (Reimers and Cassatella 1985), we obtain an accretion luminosity (for an average mass white dwarf, $M_{WD} = 0.6$ $M_\odot$), of $L_{acc} = 7.9 \times 10^{33}$ erg s^{-1}.

The condition for disk formation (eq. 12) gives $V_{rel} \lesssim 1.4 \times 10^6$ cm s^{-1}, which is satisfied for our assumed parameters. Thus, disk formation is possible for the Mira AB system. This is consistent with the observations of Reimers and Cassatella (1985) and Cassatella et al. (1985), which implied the existence of a disk around Mira B. Mira has been detected in soft x-ray (0.15-2.5 kev), with a luminosity (for an assumed distance of 114 pc) of $L_x \simeq 2.3 \pm 0.8 \times 10^{29}$ ergs s^{-1} (Jura and Helfand 1984). These authors tried to argue that the low value of the x-ray luminosity suggests that Mira B is a main sequence star. However, in view of the many uncertainties, the accretion luminosity we obtained should be regarded as consistent with the lower limit on the Mira B luminosity, $L_B > 3.3 \times 10^{32}$ ergs s^{-1} (Reimers and Cassatella 1985). The fact that a wind fed disk can form in the system, can explain the low x-ray luminosity.

GX 1 + 4

This known bright galactic binary x-ray source is often mentioned as a neutron star powered by wind accretion (e.g. Garcia 1986). It has a spin period of 122 sec and a spin-up rate of $|\dot{P}/P_s| = 7.0 \times 10^{-10}$ s^{-1} (Elsner et al. 1985). The value of the relative velocity required to produce such a spin-up rate (eq. 15) $V_{rel} = 4.6 \times 10^7$ $(P_{orb}/1d)^{-1/4}$ cm s^{-1} appears too low.

Also, the extremely smooth spin-up behaviour (Fig. 3) is in direct conflict with the non-steady behaviour expected for wind accretion. A fluctuating spin-up is expected both because of the non steady nature of the flow, as described in section 2, and because of the ionization feedback of the x-rays on the wind, as found by Ho and Arons (1987). We thus conclude that GX 1+4 is very probably powered by disk accretion resulting from Roche lobe overflow.

5. CONCLUSIONS

Recent calculations have shown that accretion from a stellar wind is very probably unsteady, leading to fluctuations in both the mass and angular momentum accretion rates. While the average mass accretion rate is described quite adequately by the Bondi-Hoyle theory, the average rate of accretion of angular momentum is considerably lower (by about a factor 5) than the rate at which angular momentum is deposited into the symmetric accretion cylinder. This makes (quasi-steady) disk formation from wind accretion very difficult. A combination of x-ray, uv, and optical observations of symbiotics, x-ray binaries, and related systems can be used to determine the existence of such a disk, thus providing a better understanding of the accretion process.

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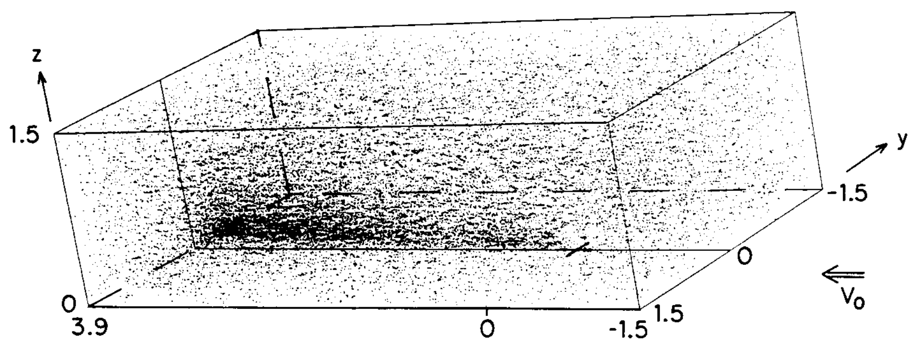

Fig. 1. The instantaneous location of the particles for accretion from an inhomogeneous medium. The cross marks the accreting object.

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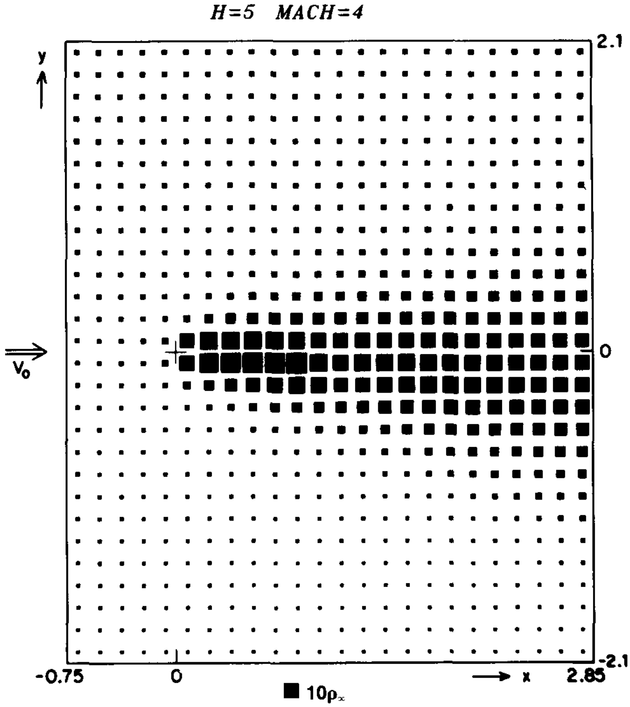

Fig. 2. The density profile for an isothermal flow. H is the scale of the density gradient (in units of the accretion radius).

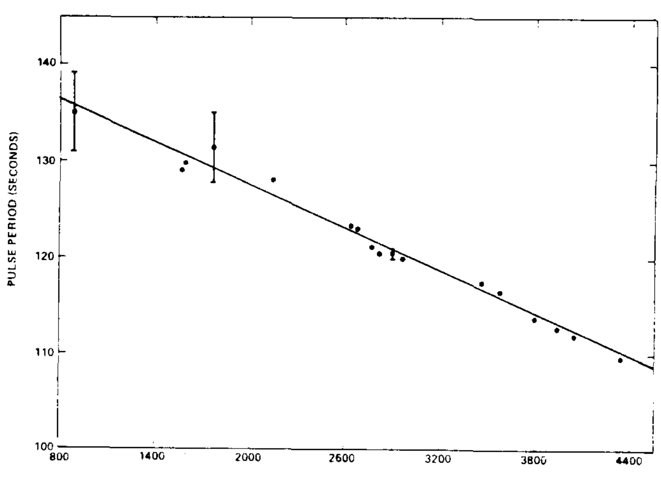

Fig. 3. The x-ray pulse period history of GX 1+4, taken from Elsner et al. (1985).

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