the structure of the accretion disk. This requirement can be verified only when more is known about the interactions at the Alfvén radius.

Finally, this model imposes some conditions on the properties of the plasma in the accretion column. Limits on turbulence and convection during the descent are required so that variations in the density of the infalling plasma are not smoothed out beyond the timescale of features observed in the Her X-1 pulse profile (rise time $\approx$ 50 ms). Since the total free-fall time from R_{Alf} to the surface of the neutron star is $\approx$ 100 ms, this condition would be violated only by very largescale effects in the column or by significant delays at shock fronts or deceleration zones. The model further demands that each spurt of plasma cool within $\approx$ 50 ms. This has been substantiated by preliminary calculations[8].

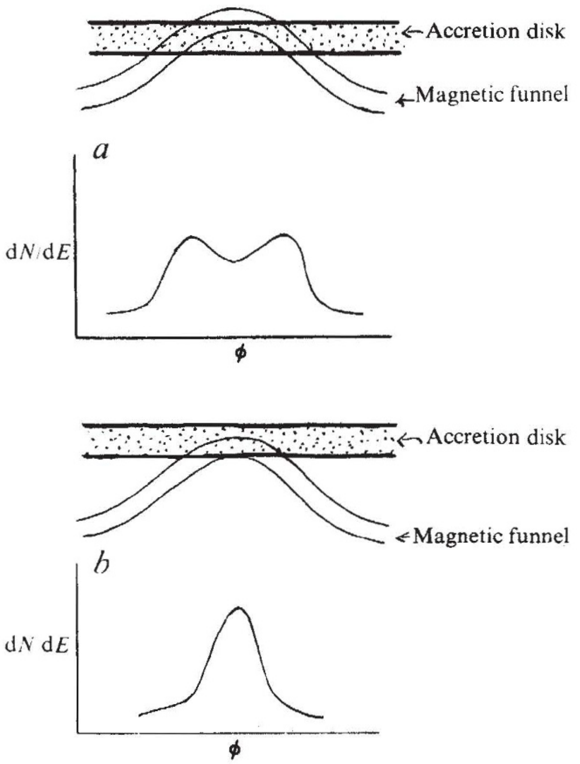

Fig. 2 Relative position of magnetic funnel and accretion disk as a function of phase, and the resulting pulse shape: *a*, double-peaked pulse; *b*, single-peaked pulse after precession of the neutron star or accretion disk.

None of the conditions listed here seem insurmountable, though several may warrant further investigation.

Since the rotation axis and the accretion plane are not perpendicular in this model, either the neutron star or the accretion disk will be precessing. Precession has been proposed by several authors as the source of the 35-d periodicity of Her X-1[8,9,11]. Evidence for variation in the shape of the 1.24 s pulse across the 35-d cycle would provide strong evidence for the present model. Qualitatively, it predicts the secondary minimum to be more pronounced in the middle of the 9-d 'on' state, and more single-peaked pulses to be observed at the beginning and end of each 'on' state (Fig. 2*a* and *b*).

Short term variations in pulse shape and intensity ($\approx$ 1–10 s) observed in Uhuru sightings (unpublished) of Her X-1 may be explained in this model in terms of fluctuations in accretion disk density. The fluctuation frequency is expected to be roughly equal to the orbital period at R_{Alf}, $t \approx 2\pi\,(GM/R^3_{Alf})^{1/2} \approx 1$ s (ref. 10), as observed. This model, like the standard model, cannot easily account for reported asymmetries in the pulse profile.

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Cosmological effects of primordial black holes

ALTHOUGH only black holes with masses $\gtrsim 1.5 M_\odot$ are expected to result from stellar evolution[1] black holes with much smaller masses may be present throughout the Universe[2]. These small black holes are the result of density fluctuations in the very early Universe. Density fluctuations on very large mass scales were certainly present in the early universe as is evident from the irregular distribution of galaxies in the sky[3]. Evidence of density fluctuations on scales smaller than the size of galaxies is generally thought to have been destroyed during the era of radiation recombination[4]. But fluctuations in the metric of order unity may be fossilised in the form of black holes. Observation of black holes, particularly those with masses $M < M_\odot$, could thus provide information concerning conditions in the very early Universe.

One indication that many black holes exist at present in the Universe is the evidence that the average density of matter in the Universe greatly exceeds the observed density of matter. Application of the virial theorem to galactic clusters[5] implies that the density of matter is at least five times the observed density. Measurements of the deceleration[6] and positions[3] of galaxies suggest that the density of matter may be larger than the observed density by a factor $\sim$100—perhaps enough to make the Universe closed, although these measurements are rather uncertain. On the other hand, there are reasons[7] for believing that the observed deuterium in the Universe was formed in the early radiation era. This would place an upper limit on the free nucleon density during the first 15 min of the Universe. This upper limit on the nucleon density implies that the present-day matter density $\lesssim 6 \times 10^{-31}\text{cm}^{-3}$; that is, $\sim$10 times the observable matter density. This upper limit on the total matter density would be consistent with applications of the virial theorem to galactic clusters but would not be consistent with the above-mentioned measurements suggesting a higher density. If evidence for a cosmologically flat or closed Universe holds up then it follows that during the first 15 min most of the matter in the universe must have existed in some other form than free nucleons—in other words, black holes.

If many small black holes ($M < M_\odot$) exist at the present time then their presence may be revealed because they radiate electromagnetic radiation. Indeed, during collapse the metric will be changing rapidly on a time scale $\tau \simeq 10^{-5}\,(M/M_\odot)$ s, so that production of massless particles with energy of order h/τ is expected[8]. Thus masses smaller than about 10^{20} g will radiate X rays and gamma rays when they undergo gravitational collapse. Hawking[9] has suggested that the emission of massless particles can be interpreted by saying that black holes have a temperature $\sim 10^{-6}$ $(M_{\odot}/M)$ K. This interpretation implies that black holes with masses as large as 10^{15} g would have radiated away all their mass by now. Davies and Taylor[10] have, however, suggested that the emission of radiation from a black hole only takes place for a brief instant during the collapse and that only black holes with mass $\lesssim 10^{-4}$ g will radiate away a significant fraction of their mass. If they are correct then practically all radiation due to black holes would have been emitted in the very early Universe and at the present time would only show up as a possible contribution to the 3 K microwave background.

On the other hand, if Hawking's interpretation is correct then small black holes would have produced X- and gamma-radiation up to and including the present time. If the black hole mass spectrum is not varying too rapidly the result would be background radiation the spectrum of which started out as a continuation of the 3 K blackbody spectrum and rose slowly to a peak at an energy determined by the smallest black hole mass now existing. Observational evidence for Hawking's interpretation might be provided by a distortion in the 3 K blackbody spectrum for wavelengths <1 cm or by a peak in the isotropic X-ray background above 10 MeV (corresponding to Hawking's estimate of 10^{15} g as the smallest black hole mass now existing). A flattening of the isotropic X-ray background spectrum at about 30 MeV has, in fact, been reported[11]. If we identify the measured X-ray flux associated with this feature ($\sim 10^{-6}$ photons cm^{-2} s^{-1} keV^{-1}) with X-ray emission from black holes with masses in the neighbourhood of 10^{15} g then one arrives at a space density of these black holes $N_{max} \approx 10^{-52}$ cm^{-3}. Because the present-day spatial density of galaxies is about 10^{-75} cm^{-3} we conclude that there may be as many as 10^{23} small black holes per galaxy. If we assume that the volume of our Galaxy is 10^{12} pc^3 then a region the size of our Solar System ($\sim 10^{44}$ cm^3) might contain several small black holes. Of course, there are other possible interpretations[12,13] of the 30 MeV feature in the X-ray background and therefore the actual spatial density of small black holes may be much less than N_{max}.

In order to calculate the contribution of small black holes to the total mass of the Universe one must make some assumption about the primordial black hole mass spectrum. The simplest assumption that can be made is that the number of black holes in each logarithmic interval of mass is the same:

$$\mathrm{d}N = N_0 \mathrm{d}M/M \qquad (1)$$

This assumption is consistent with the idea[14] that perturbations of the metric in the early Universe should be independent of scale length.

With the mass spectrum (1) the total mass of primordial black holes is $N_0 M_{max}$ where M_{max} is the maximum mass of a primordial black hole. Taking $N_0 = N_{max}$ and a present-day mass density $\lesssim 10^{-30}$ g cm^{-3} gives $M_{max} \lesssim 10^{22}$ g. This maximum mass for primordial black holes may be related to the Hubble mass at the time when black hole formation in the early Universe stopped. It is interesting that the Hubble mass was equal to 10^{22} g at some time during the hadron era ($t < 10^{-4}$ s) when large density fluctuations are 'predicted' to occur in some theories of dense hadronic matter[15]. Conversely, identification of any of the cosmological effects we have discussed as being the result of small black holes should provide some information on the nature of dense hot hadronic matter. A search for evidence of small black holes in the Solar System might be very worthwhile. Indeed, the existence of small black holes in the Solar System might have considerable economic significance because small black holes would be very useful as power sources[16].

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ATS-6 radio beacon experiment

SINCE ATS-6 was launched into a geostationary orbit at 94°W in late May 1974, measurements of the total electron content (TEC) using the Faraday polarisation-rotation[1] and group dispersive-delay techniques have been made at Fort Monmouth (40.18°N; 74.06°W). Comparison of TEC rate of change obtained by the two techniques yields the temporal variation of the integrated number of free electrons above the ionosphere. This variation indicates a flow of electrons from regions above the ionosphere into the ionosphere at night, while during the day the direction of flow is reversed. The rate of the electron flux is estimated using the continuity equation.

The total Faraday[1] rotation from the signal source to the observer is related to the total electron content by the expression:

$$\begin{aligned} a &= (k/f^2) \int B \cos\theta N \mathrm{d}s \\ &= (k/f^2) \int (B \cos\theta \sec\chi) N \mathrm{d}h \qquad (1) \\ &= (k/f^2)\, \overline{M}\, N_I \end{aligned}$$

where $k = 2.36 \times 10^{-5}$, M is the magnetic field factor (at 420 km), N_I is the total ionospheric electron content, and $f =$ 140 MHz. As B decreases inversely with the cube of the geocentric distance and the electron density decreases exponentially with altitude above F_2 (max) (~ 300 km), the rotation is heavily weighted near the Earth and is considered to provide electron content values below $\sim$ 1,200 km.

Using the dispersive-group-delay technique[2], the phase of the modulation envelope between a carrier and its sideband is compared at two frequencies (nominally $f_{1,2} = 140, 360$ MHz with a sideband displacement of $\Delta f = 1$ MHz). Since the phase is insensitive to the Earth's magnetic field, this technique yields the number of electrons along the entire path from satellite to observer (N_T).

The differential modulation phase $\Delta\varphi$, in degrees, is:

$$\Delta\varphi/360 = 40.3 \Delta f/c \sec\chi (f_1^{-2} - f_2^{-2}) N_T \qquad (2)$$

where c is the speed of light *in vacuo*, and χ is the zenith angle.

The relative variation of the total electron content measured by the Faraday and group-delay techniques is shown in Fig. 1*a* and *b* at 15-min intervals for the time period 1600 EDT on July 3 to 0800 EDT on July 8. The temporal variations of N_I and N_T were nearly parallel with most density variations observed on both curves. In general, $\Delta N_I/\Delta t$ and $\Delta N_T/\Delta t$ varied between $\pm 1 \times 10^{16}$ electrons m^{-2} per 15-min interval.

Large increases of total electron content, in response to two large solar flares, are prominent during the time period covered by Fig. 1. Between 0945 EDT and 1000 EDT on July 4, N_I increased by $\sim 1.5 \times 10^{16}$ electrons m^{-2}, while N_T increased by $\sim 2 \times 10^{16}$ electrons m^{-2}. Since the content values in Fig. 1*a* and *b* are given every 15 min, the full increase of N_I and N_T is not indicated there. Starting at $\sim$ 0953 EDT, N_I increased by $\sim 3.3 \times 10^{16}$ electrons m^{-2} in 3 min and then decayed to its figure value at 1000 EDT. At the same time, N_T increased by approximately