THE ASTROPHYSICAL JOURNAL, 364:198–202, 1990 November 20

TeV GAMMA-RAY PRODUCTION IN ACCRETING BLACK HOLE SYSTEMS

PATRICK SLANE
Harvard-Smithsonian Center for Astrophysics
AND
SANJAY M. WAGH
Tata Institute of Fundamental Research
Received 1990 March 29; accepted 1990 May 18

ABSTRACT

Plasma accreting onto a black hole carries with it magnetic flux which is deposited on the black hole horizon. The accumulated flux results in a black hole magnetosphere similar to that found surrounding a magnetic neutron star in an accreting binary system. Potential differences in the magnetosphere can result in acceleration of charged particles in the outer magnetosphere. For sufficiently large voltages, protons accelerated in such regions may produce a flux of γ-rays from the decay of neutral pions resulting from *p-p* collisions. Matter from the inner disk region may provide an efficient target for such beam-dump γ-ray production. Such a mechanism could result in a periodicity associated with the orbital motion of the target material.

Subject headings: black holes — gamma rays: general — radiation mechanisms

I. INTRODUCTION

The energetic processes associated with compact objects owe their existence, ultimately, to the tremendous gravitational potentials and, in many cases, magnetic fields available in such objects. In particular, compact objects which are surrounded by disks of accreting matter act as powerful sources of X-ray emission associated with the heating of the disk material as it is compressed upon infall. X-ray pulsars, on the other hand, may accelerate charged particles to enormous energies by virtue of powerful magnetic fields. In the case of accreting binary systems in which the central compact object is a magnetic neutron star or white dwarf, we may find both effects in action. Indeed, such objects may be the source of a large fraction of Galactic cosmic rays.

Black holes (BHs) which accrete matter from a disk may develop a surrounding environment similar to that found in the vicinity of accreting magnetic neutron stars. In particular, when the accreting material carries with it frozen-in magnetic flux (as may be expected during accretion from a companion star, for example) a magnetosphere surrounding the BH may be formed as flux is deposited on the horizon (Thorne, Price, and Macdonald 1986, hereafter TPM). For sufficiently large field strengths, voltages capable of accelerating charged particles to very high energies may develop (Lovelace 1976; TPM). The field strength, however, is critically dependent upon the conditions in the inner-disk region; as an equipartition field, the density and infall velocity of the disk matter determine the strength. Calculations of such disk parameters are highly dependent upon the assumptions made regarding the disk structure. In § II we outline the basic calculation of the field strength and discuss the results associated with the "standard" α-disk model of Shakura and Sunyaev (1973). In particular, we calculate the equipartition field for a 10 $M_\odot$ BH assuming accretion rates appropriate for the BH candidates Cyg X-1, A0620−00, and LMC X-3. In § III we discuss the particle acceleration voltages available in such systems and, based upon the disk parameters developed in § II, we investigate the plausibility of γ-ray production resulting from decay of neutral pions produced in collisions of such high-energy particles with matter from the accretion disk. In § IV we summarize the results of calculations using the "hot disk" models of Payne and Eardley (1977) and White and Lightman (1989*a*, *b*). Finally, in § V we discuss the results in terms of observable fluxes and suggest further calculations to more fully characterize the possible signatures of any such particle acceleration in these systems.

II. MAGNETOSPHERE IN ACCRETING BH SYSTEM

A BH which is a member of a binary system may accrete matter from the companion star. For a Roche-lobe filling companion, the accretion may proceed through formation of a thin disk. The disk plasma will carry with it magnetic flux which will be deposited on the BH horizon. While the accreted field lines will be randomly oriented, the net accreted field will build up in random-walk fashion (TPM). Over sufficient time, the field will reach equipartition whereby the magnetic energy density associated with the ram pressure at the inner edge of the disk is equal to the accretion energy density (see, e.g., Shapiro and Teukolsky 1983):

$$\frac{B^2}{8\pi} = \frac{1}{2}\rho(r_0)v_r^2(r_0) , \qquad (1)$$

where r_0 is the distance to the inner edge of the disk and v_r is the radial infall velocity of the accreting matter. The parameters defining this condition depend critically on the inner-disk structure.

To estimate the magnitude of the equipartition field as well as the disk density in the inner regions, we may use the "standard" α-disk model (Shakura and Sunyaev 1973). In particular, we consider the secenario in which the inner disk region is gas pressure dominated with the opacity dominated by free-free absorption. The density may then be written as

$$\rho = 3 \times 10^2 \alpha^{-7/10} \dot{M}_{17}^{11/20} M_1^{-5/4} r^{-15/8} f^{11/20} \text{ g cm}^{-3} , \qquad (2)$$

where $\dot{M}_{17}$ is the accretion rate in units of 10^{17} g s^{-1}, M_1 is the mass of the central BH in solar masses, and r is the distance from the BH in units of the gravitational radius, i.e.,

$$r = \frac{R}{R_g} = \frac{Rc^2}{GM} . \quad (3)$$

The unknown quantity α is introduced to parameterize the viscosity in the disk ($\alpha \lesssim 1$), and

$$f = 1 - \left(\frac{6}{r}\right)^{1/2} . \quad (4)$$

The disk thickness is given (in cm) by

$$h = 5 \times 10^2 \alpha^{-1/10} \dot{M}_{17}^{3/20} M_1^{3/4} r^{9/8} f^{3/20} . \quad (5)$$

We may determine the radial infall velocity by balancing the accretion rate with the mass transfer through the inner disk:

$$v_{\rm in} = \frac{\dot{M}}{2\pi r \rho h} . \quad (6)$$

In Table 1 we list the parameters of the three primary BH candidates along with the values associated with the calculations outlined above. For each, we have assumed $\alpha = 0.1$ independent of radius, and we have neglected any effect of the magnetic fields on the viscosity. We have used a mass of 10 $M_\odot$ for each BH candidate (which, although a simplification, is consistent with current limits on the actual masses) and have derived the accretion rate based upon the X-ray luminosity:

$$\dot{M} = \frac{L r_0}{GM} . \quad (7)$$

Calculations of the inner disk structure are evaluated at a fiducial radius $r_0 = 10R_g$; this is reasonable since the innermost orbit in the disk (for a Schwarzschild BH) is at $r = 6R_g$ while the disk flux peaks at $r \sim 8R_g$. Thus, we have

$$\dot{M}_{17} = 11 L_{38} \text{ g s}^{-1} \quad (8)$$

where L_{38} is the X-ray luminosity in units of 10^{38} ergs s^{-1}. As per equation (1), fields on the order of $\sim 10^6$ G are possible for the systems under consideration (as indicated in Table 1).

Several considerations make the preceding estimate of the magnetic field strength quite tentative. Significant penetration of the field into the disk matter through Rayleigh-Taylor instabilities may preclude attaining the equipartition strength. More importantly, inner-disk conditions governing the density strongly affect the resultant field. This is particularly important in light of the hot-disk models (Payne and Eardley 1977; Shapiro, Lightman, and Eardley 1976; White and Lightman 1976; White and Lightman 1989*a*, *b*) which yield a vastly different picture of the inner disk region (see § V).

III. PARTICLE ACCELERATION IN BH MAGNETOSPHERE

The magnetosphere formed around an accreting BH is qualitatively similar to that surrounding an accreting magnetic neutron star. The electric field along $\boldsymbol{B}$-field lines threading the disk must satisfy $\boldsymbol{E} \cdot \boldsymbol{B} \approx 0$ since any nonzero component of $\boldsymbol{E}$ along $\boldsymbol{B}$ would remove electric charges from the disk until a force-free configuration was attained. However, the resulting charge distribution in the magnetosphere may yield a significant component of $\boldsymbol{E}$ perpendicular to $\boldsymbol{B}$. The resulting potential difference between $\boldsymbol{B}$ field lines may play the role of a battery which supplies power to an external astrophysical load in the weak-field region where acceleration across the field lines becomes possible. The path length for collisional diffusion across the field lines may be significantly smaller than the Larmor radius in such regions (Wagh and Dadhich 1989). A schematic representation of the process is shown in Figure 1.

The acceleration potential available through such a mechanism is (TPM)

$$\Delta V_{\rm max} \sim 10^{15} \bar{a} M_1 B_8 \text{ volts} . \quad (9)$$

Here $\bar{a} = a/\mathscr{M}$ where a is the angular momentum per unit mass of the BH and $\mathscr{M}$ is the BH mass (both in geometrized units: $\bar{a} \lesssim 1$). The power available is supplied by the hole rotation and is of order

$$W_{\rm max} \sim 10^{35} \bar{a}^2 M_1^2 B_8^2 \text{ ergs s}^{-1} . \quad (10)$$

For sufficiently large fields, then, the resultant power may be considerable. Maximum values for the acceleration potential and available power for each of the objects under consideration are tabulated in Table 1. The values for the potential are on the order of those expected in systems containing an accreting neutron star (some of which have shown strong evidence of TeV γ-ray emission) while the values for the maximum power are somewhat lower than those suggested by models involving neutron stars (e.g., $W_{\rm max} \sim 10^{35}$ ergs s^{-1} for Her X-1; see Cheng and Ruderman 1988).

One possible scenario for the production of high-energy radiation from accreting BH systems involves the acceleration of protons in the outer magnetosphere of the hole. As with outer-gap acceleration models in accreting neutron star magnetospheres (Cheng and Ruderman 1988), protons may be accelerated toward the disk where high-energy collisions result in the production of pions. The neutral pions will subsequently decay into γ-rays which may provide a signature for the ener-

TABLE 1

PARAMETERS ASSOCIATED WITH SELECTED BLACK HOLE CANDIDATES

Parameter	Symbol	Cyg X-1[a]	A0620−00[b]	LMC X-3
X-ray luminosity	L_{38}	0.2	1	3
Accretion rate[c]	$\dot{M}_{17}$	2.3	11	33
Disk density	$\rho(r_0)$ (g cm^{-3})	0.8	1.8	3.2
Disk thickness	$h(r_0)$ (cm)	4×10^4	6×10^4	7×10^4
Magnetic field	$B(r_0)$ (G)	2×10^5	5×10^5	1×10^6
Accelerating voltage	$\Delta V_{\rm max}$ (volts)	2×10^{13}	5×10^{13}	1×10^{14}
Available power	$W_{\rm max}$ (ergs s^{-1})	5×10^{31}	3×10^{32}	1×10^{33}

[a] During high state.
[b] During outburst.
[c] Assuming $M_1 = 10$; see text.

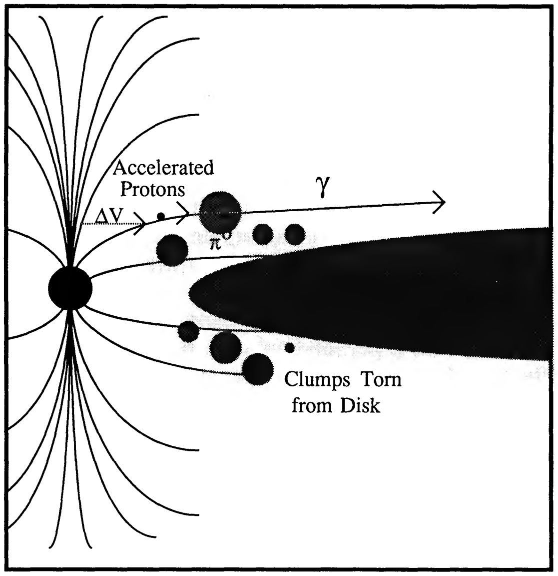

FIG. 1.—Schematic illustration of proton acceleration, and associated γ-ray production, in outer magnetosphere of BH. Conversion target may consist of clumps of matter from disk, or of disk itself (see text).

getic process. Production of such γ-rays depends upon the presence of target matter for the conversion process. Constraints on the path length presented by such target matter are fairly strict; small amounts of matter will not yield an efficient conversion process while large thicknesses will result in reabsorption of the γ-rays. As shown in Figure 2, path lengths on the order of the $p-p$ interaction length ($\lambda_p \sim 40$ g cm^{-2}) produce the most favorable flux of high-energy γ-rays (Slane and Fry 1988).

The target for production of π^0-decay γ-rays may be the accretion disk itself (Cheng and Ruderman 1988) or may consist of clumps of material torn from the disk by instabilities (Slane and Fry 1988). Given the density of inner-disk material (eq. [2]), we can estimate the target size required for efficient γ-ray production (see Fig. 1). For most efficient TeV γ-ray production, a path length $p \sim 100$ g cm^{-2} is required. For the densities shown in Table 1, this requires a target size much smaller than the inner disk thickness (e.g., ~ 125 cm for Cyg X-1 parameters).

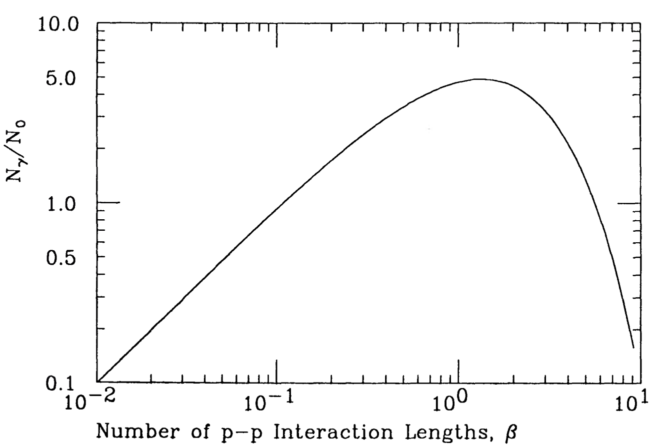

FIG. 2.—Proton to γ-ray conversion ratio. Here β represents the number of $p-p$ interaction lengths traversed. We assume an average of 10 γ-rays result from each proton interaction (each with $\sim 1/30$ of the primary proton energy). (From Slane and Fry 1988.)

TABLE 2

DISK PARAMETERS ASSOCIATED WITH HOT DISK MODELS

Parameter	Model[a]	Cyg X-1	A0620−00	LMC X-3
$B(r_0)$(G)	1	3×10^6	7×10^6	1×10^7
	2	6×10^5	2×10^6	3×10^6
	3	4×10^5	1×10^6	2×10^6
ΔV_{max} (volts)	1	3×10^{14}	7×10^{14}	1×10^{15}
	2	6×10^{13}	2×10^{14}	3×10^{14}
	3	4×10^{13}	1×10^{14}	2×10^{14}
W_{max} (ergs s^{-1}) ...	1	7×10^{33}	5×10^{34}	2×10^{35}
	2	3×10^{32}	3×10^{33}	1×10^{34}
	3	2×10^{32}	1×10^{33}	4×10^{33}

[a] Model 1, pure bremsstrahlung. Model 2, low-z two-temperature Comptonized bremsstrahlung. Model 3, high-z two-temperature Comptonized bremsstrahlung.

IV. ALTERNATIVE DISK MODELS

The discussion given above pertains to disk parameters derived from the disk solution of Shakura and Sunyaev (1973) which are appropriate for a cold, optically thick disk. However, such a disk model fails to account for the hard X-ray emission observed from sources such as Cyg X-1. Alternative models, such as the hot-disk models wherein the inner regions of the disk are optically thin and at high temperature, are required to provide a consistent picture. To gain a view of the γ-ray production scenario under conditions associated with such alternative disk models, we illustrate in Table 2 the expected equipartition fields as derived from the densities and infall velocities described in three such models. The first is the pure bremsstrahlung disk outlined by Payne and Eardley (1977) in which the disk is assumed to be optically thin and supported by gas pressure. The disk density and thickness are then given by

$$\rho = 8.5 \times 10^{-3} \dot{M}_{17}^{1/4} M_1^{-5/4} r^{-15/8} g^{1/4} \text{ g cm}^{-3} , \quad (11)$$

$$h = 1.3 \times 10^4 \dot{M}_{17}^{1/4} M_1^{3/4} r^{9/8} g^{1/4} \text{ cm} , \quad (12)$$

where

$$g = \frac{r^{1/2} - 2.45}{0.71} . \quad (13)$$

As shown in Figure 3, such disks are considerably thicker, with correspondingly lower densities, than for the optically thick case. The equipartition fields, and thus the available acceleration voltages and maximum power, are somewhat larger for the (more realistic) optically thin disks. Further, the path length presented by a reasonable fraction of such disks is sufficient for efficient TeV γ-ray production from high-energy protons.

In the optically thin case, the electron temperatures may exceed the electron rest mass. At such high temperatures, the effects of pair-production may then play an important role in determining the inner disk structure. White and Lightman (1989*a*, *b*) have considered the effects of electron-positron pairs in hot accretion disks for a variety of cases. They find that, for $\alpha \sim 0.1$ and $\dot{m} \gtrsim 0.01$ (where $\dot{m} = \dot{M}c^2/L_{\rm Edd}$ is the dimensionless accretion rate), the disk is described by a two-temperature Comptonized bremsstrahlung model. For accretion rates lower than some critical value ($\dot{m}_{\rm cr} \sim 0.6$ for $\alpha \sim 0.1$; White

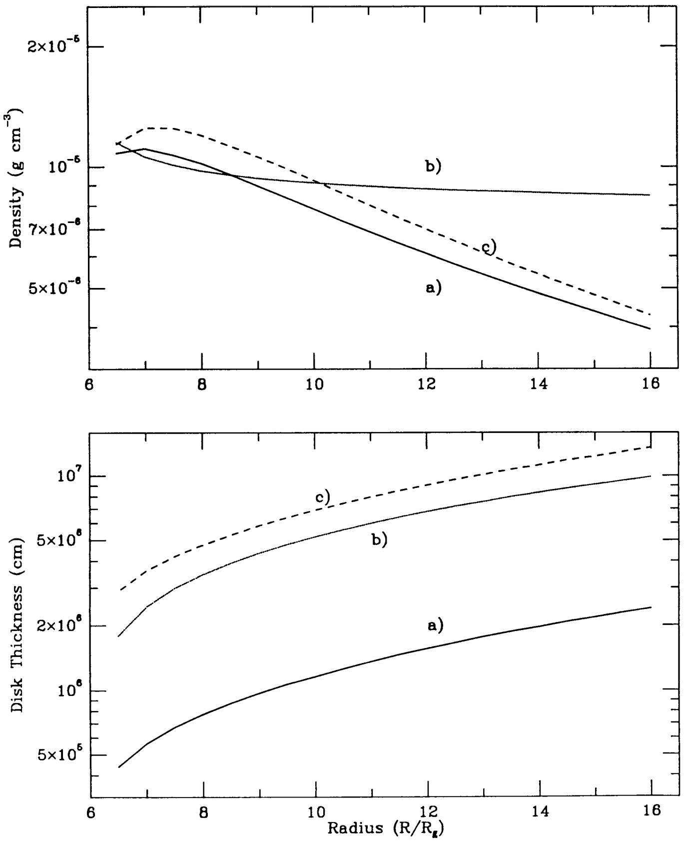

FIG. 3.—Comparison of disk structure associated with various hot-disk models (each with parameters appropriate for Cyg X-1): (*a*) pure bremsstrahlung (Payne and Eardley 1977), and two-temperature Comptonized bremsstrahlung for (*b*) low-z and (*c*) high-z (White and Lightman 1989*b*).

and Lightman 1989*b*) they find that two solutions exist for the disk structure. In the first, low-z, solution (where $z = n_+/n_p$ is the ratio of positron to proton number density) the disk density and thickness are given by

$$\rho = 1.8 \times 10^{-4} \alpha^{7/15} \dot{M}_{17}^{-2/15} M_1^{-13/15} f^{-2/15} \text{ g cm}^{-3} , \quad (14)$$

$$h = 6 \times 10^4 \alpha^{-22/45} \dot{M}_{17}^{17/45} M_1^{28/45} r^{14/15} f^{17/45} \text{ cm} . \quad (15)$$

Magnetic fields and acceleration voltages for this model are shown in Table 2. The disk structure is plotted in Figure 3.

In the case of strong pair-production (high-z), the disk structure is described by

$$\rho = 0.28 \alpha^{13/15} \dot{M}_{17}^{2/5} M_1^{-7/5} r^{-21/10} f^{2/5} \text{ g cm}^{-3} , \quad (16)$$

$$h = 4.9 \times 10^3 \alpha^{-6/5} \dot{M}_{17}^{1/5} M_1^{4/5} r^{6/5} f^{1/5} \text{ cm} . \quad (17)$$

Here we have taken the case where the dimensionless electron temperature $\Theta_e = kT_e/m_e c^2$ is ~ 1 (which is the only self-consistent solution). This high pair density configuration is unstable, however. White and Lightman (1989*b*) find that if the hot disk is perturbed to $z \gtrsim 1$, pair runaway will occur and the perturbed region will collapse toward an optically thick configuration. Thus, the disk may assume such a configuration for only brief episodes. The disk parameters associated with the high-z solution are summarized in Table 2 and plotted in Figure 3.

V. DISCUSSION

To obtain a crude estimate of the γ-ray flux (i.e., photons cm^{-2} s^{-1}) that could result given the production mechanism outlined above, we merely assume that the entire power derived from the calculations is ultimately radiated in the form of TeV γ-rays. Using the assumed distances listed in Table 3, along with the largest estimates of the available power as calculated above, we find the values also listed in Table 3. We note that the flux range listed (3×10^{-10} to 4×10^{-13} cm^{-2} s^{-1}) is, at the high end, compatible with current TeV detection sensitivities (e.g., for the Crab, a flux $F_\gamma \sim 7 \times 10^{-11}$ cm^{-2} s^{-1} above 0.4 TeV is sufficient to yield a 15 σ excess in a 33 hr observation Weekes *et al.* 1989). Further, the calculated flux assumes isotropic emission; if the signal is beamed, these fluxes may be underestimates. Realistically, of course, a more complete treatment may yield fluxes below current sensitivities (and we note that the most favorable flux corresponds to the outburst state of A0620−00 which has not been observed again since the time of its discovery).

We note that, if the γ-rays are produced by collisions in clumps released from the accretion disk, then modulation of the signal at the orbital period of the clump matter may exist. Given such a scenario, we may estimate the range of periods which could be present in a typical system. The period for a Keplerian orbit at a distance R from a mass M is given by

$$P = \left(\frac{4\pi^2}{GM}\right)^{1/2} R^{3/2} . \quad (18)$$

Again using parameters associated with typical BH systems, we find periods on the order of 10^{-3}–10^{-4} s. We have ignored time dilation effects (which may be $\sim 10\%$); the values are useful, at any rate, for purposes of choosing a range in frequency space about which to search for periodic behavior. Any such actual periodicity may be complicated by the changing geometry as the clumps of matter are being accreted. This could lead to an effective period derivative or, equivalently, to a smearing of the associated γ-ray light curve. Also, the duration of such an episode will be associated with the time scale over which target matter of sufficient path length is available for the mechanism to operate. The time scale may be dominated by several factors including the time required for accretion and the time associated with dissipation of the clumps by tidal or other forces (which may be quite short for such short orbital periods).

Finally, it is worth noting that, for sufficiently thick target regions, electromagnetic cascades may degrade the photon energies significantly. Such reduction, of course, would be

TABLE 3

ESTIMATED TeV γ-RAY FLUXES

Parameter	Symbol	Cyg X-1	A0620−00	LMC X-3
Distance	d (kpc)	2	0.9	50
Available power	W_{max} (volts)	7×10^{33}	5×10^{34}	2×10^{35}
Flux at Earth	F_{max} (cm^{-2} s^{-1})	9×10^{-12}	3×10^{-10}	4×10^{-13}

accompanied by an increase in the number of photons produced. Detailed cascade calculations, making use of the inner disk structure predicted with the models mentioned above, may prove useful in estimating lower energy fluxes in terms of *Gamma Ray Observatory* (GRO) sensitivities (see, e.g., Stanev and Vankov 1989).

In summary, we have performed simple calculations to investigate the inner-disk and magnetosphere region of an accreting BH system. We find that, using reasonable system parameters, an environment may exist in which charged particle acceleration could produce an observable flux of very high energy γ-rays. We have suggested that any such energetic signal could exhibit periodic behavior indicative of orbital motion in the inner disk. Such periodicity would enhance the probability of detection and could provide information on the mass of the central BH.

The authors would like to thank A. Szentgyorgyi and J. McClintock for their useful comments and suggestions on the text.

REFERENCES

Cheng, K. S., and Ruderman, M. 1989, *Ap. J. (Letters)*, **337**, L77.
Lovelace, R. V. E. 1976, *Nature*, **262**, 649.
Payne, D. G., and Eardley, D. M. 1977, *Ap. Letters*, **19**, 39.
Shakura, N. I., and Sunyaev, R. A. 1973, *Astr. Ap.*, **24**, 337.
Shapiro, S. L., Lightman, A. P., and Eardley, D. M. 1976, *Ap. J.*, **204**, 187.
Shapiro, S. L., and Teukolsky, S. A. 1983, *Black Holes, White Dwarfs, and Neutron Stars* (New York: Wiley).
Slane, P., and Fry, W. F. 1989, *Ap. J.*, **342**, 1129.
Stanev, T., and Vankov, H. P. 1989, *Ap. J.*, **343**, 828.
Thorne, K. S., Price, R. H., and Macdonald, D. A., eds. 1986, *Black Holes: The Membrane Paradigm* (New Haven: Yale University Press) (TPM).
Wagh, S. M., and Dadhich, N. 1989, *Phys. Repts.*, **183**(4), 137.
Weekes, T. C., *et al.* 1989, preprint.
White, T. R., and Lightman, A. P. 1989*a*, *Ap. J.*, **340**, 1024.
———. 1989*b*, preprint.

P. SLANE: Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138

S. M. WAGH: Theoretical Astrophysics Group, Tata Institute of Fundamental Research, Bombay 400 005, India