NASA

Technical Memorandum **79649**

(NASA-TM-79649) GAMMA RAYS FROM ACCRETION ONTO ROTATING BLACK HOLES (NASA) 10 p HC A02/MF A01 CSCL 03A

N79-23854

Unclas

G3/89 25913

Gamma Rays from Accretion onto Rotating Black Holes

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September 1978

National Aeronautics and
Space Administration

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GAMMA RAYS FROM ACCRETION ONTO ROTATING BLACK HOLES

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Running Title: Gamma Rays from Rotating Black Holes

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Submitted to: Main Journal

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SUMMARY

Ionized matter falling onto an isolated, rotating black hole will be heated sufficiently that proton-proton collisions will produce mesons, including neutral pions, which decay into γ rays. For massive (10^3 $M_\odot$) black holes, the resulting γ-ray luminosity may exceed 10^{36} ergs s^{-1}, with a spectrum peaked near 20 MeV.

Key Words: Gamma-ray astronomy, gamma-ray sources, black holes

INTRODUCTION

The discovery of several localized γ-ray sources which have no apparent x-ray counterparts (Thompson et al. 1977; Hermsen et al. 1977) has led to renewed interest in physical mechanisms which would produce a significant flux of γ-rays without an energy spectrum extending into the x-ray energy band. Dahlbacka, Chapline, and Weaver (1974) have shown that accretion of matter onto an isolated, non-rotating (Schwarzschild) black hole may produce γ rays with a spectrum peaked near 18 MeV. The present work extends this calculation to the case of matter accreting onto an isolated, rotating (Kerr) black hole and shows that the γ-ray luminosity may exceed 10^{36} ergs s^{-1} for accretion onto a rapidly rotating $10^{3} M_{\odot}$ black hole.

CALCULATION OF GAMMA-RAY PRODUCTION

As interstellar gas falls onto a black hole, it may be heated by compression. If a weak magnetic field is frozen into the gas, the accretion may be regarded as a hydrodynamic flow (Schwartzman 1971; Shapiro 1973). A significant fraction of the gravitational potential of the gas is then converted to thermal energy. If the black hole is not too massive($\lesssim 10^{4} M_{\odot}$), very little of this thermal energy is radiated away, and hence the compression may be considered as nearly adiabatic (Schwartzman 1971; Shapiro 1973). The x-ray luminosity of this process is, therefore, relatively small.. If the infalling gas is initially ionized, its temperature may exceed 10^{11} K near the Schwarzschild radius (Shapiro 1973). These temperatures are sufficiently large that proton-proton collisions have energy above the threshold for pion production. Gamma rays will then be produced by the decay of the neutral pions.

The above description is the same as for the static case (Dahlbacka, Chapline, and Weaver 1974). A rotating black hole, however, is surrounded by an ergosphere (the region inside the static limit but outside the event horizon) in which the infalling matter will spiral and accumulate before falling through the event horizon. The density of matter (and hence the temperature and probability of pion producing collisions) is very much greater in the ergosphere than in the region surrounding a static black hole. As a good approximation, then, it is possible to treat the region outside the static limit of the rotating black hole in exactly the same way as the static case, while the region within the ergosphere must be treated more carefully.

The equation for radial infall along the equator of the black hole is (Bardeen 1973)

$$\left\{\frac{dr}{d\tau}\right\}^2 = r^{-3}\left\{(r(r^2+a^2) + 2a^2m)\,E^2 - 4amE\Phi - (r-2m)\Phi^2 - \Delta r\mu^2\right\} \qquad (1)$$

where r = radial distance from the black hole

m = mass of the black hole

a = angular momentum of the black hole per unit mass of the black hole, taken to be = m for an extreme example

τ = proper time per unit mass

E = energy with respect to infinity = 1.3 GeV

μ = rest mass of the infalling particle = 1 GeV

Φ = angular momentum with respect to infinity = 0.5 $m\mu$

$\Delta = r^2 - 2\,mr + a^2$

Integrating this equation by binomial expansion of the bracket function to fourth order yields a value for the infall time of $1.25\times10^{-3}\,\frac{M}{M_\odot}$ s. This time is short compared to the electron-ion coupling time. The product of this infall time and the spherical accretion rate (Novikov and Thorne 1973) gives a total mass in the ergosphere of

$$M_{\mathrm{ergosphere}} \cong 2 \times 10^{8} \left(\frac{M}{M_\odot}\right)^{3} \rho_\infty \qquad (2)$$

where M is the mass of the black hole in units of solar mass and ρ_∞ is the density of the gas before accretion. The assumption has been made that the interstellar gas has no net velocity with respect to the black hole. The average density of protons in the ergosphere for this extreme case is, therefore, $\sim 2 \times 10^{15}\ \rho_\infty$ protons cm^{-3}. Since the accretion is nearly adiabatic, the average temperature in this region is determined from the adiabatic temperature-density relationship

$$T \propto \rho^{\,\Gamma-1} \qquad (3)$$

where Γ is the adiabatic index. For these non-relativistic protons, Γ may be taken to be 5/3, and the average temperature in the ergosphere is $\bar{T}_{\mathrm{ergosphere}} \sim 1$ GeV, for $\rho_\infty \sim 1\ \mathrm{cm}^{-3}$. The rate of π° production in a hot gas with proper density is given by (Dahlbacka, Chapline, and Weaver 1974)

$$R_{\pi^\circ} = \frac{\rho^2}{2} \langle\pi_o\rangle\ \overline{\sigma\nu(\theta)} \qquad (4)$$

where $\langle\pi_o\rangle$ is the average number of neutral pions produced per collision and $\overline{\sigma\nu(\theta)}$ is related to the laboratory pion cross section by (Dahlbacka, Chapline and Weaver 1974)

$$\overline{\sigma\nu(\theta)} = \iint \sigma(E_L)\nu_L\ F(\vec{p}_1)\ F(\vec{p}_2)\ d\vec{p}_1\ d\vec{p}_2. \qquad (5)$$

where ν_L is the laboratory velocity and F is the relativistic Maxwellian distribution. Taking $\overline{\sigma\nu(\theta)} \sim 10^{15}\ \mathrm{cm}^3\ \mathrm{sec}^{-1}$ and $\langle\pi°\rangle \sim 1$ for T $\sim$ 1 GeV one can estimate the total number of γ-rays released from the ergosphere by

$$N_\gamma \cong 2 \times 10^{15} \int V_{erg}\ \pi_{\mathrm{escape\ cone}}\ d\ V_{erg} \left(\frac{M}{M_\odot}\right)^3 \rho_\infty^{\ 2} \ \text{photons/sec} \quad (6)$$

where V_{erg} is the volume of the ergosphere and the escape cone (Zeldovich and Novikov 1971) takes into account the fact that some of the γ rays will follow trajectories into the black hole while others will escape. The fraction of those which escape is about 0.5.

Because a detailed density distribution has not been developed in this treatment, it is impossible to obtain a characteristic energy spectrum. However, the peak of the spectrum can be determined. If the radial and gravitational redshifts are considered

$$\omega = \omega_0 \ \frac{1-\beta}{1+\beta}^{\frac{1}{2}} \left\{1 - \frac{r_g}{r}\right\}^{\frac{1}{2}} \ . \quad (7)$$

where β = V/C corresponds to the 1 GeV kinetic energy of the protons, r_g is the gravitational radius and ω_0 corresponds to 68 MeV, the rest frame energy of the γ rays resulting from $\pi°$ decay. Assuming that the density - escape cone product is a maximum near $r \sim r_g = m$, the peak of the spectrum is found to be $\sim$ 20 MeV for a 1 GeV proton.

Assuming an average photon energy of 20 MeV, the γ-ray luminosity of an accreting, rotating black hole of mass M is given by

$$L_\gamma \simeq 2 \times 10^{27} \left\{\frac{1\mathrm{eV}}{T_\infty}\right\}^3 \left\{\frac{M}{M_\odot}\right\}^3 \rho_\infty^{\ 2} \ \text{ergs sec}^{-1} \quad (8)$$

where T_∞ and ρ_∞ are the temperature (in eV) and density (in protons cm^{-3}) of the gas before infall. Hence, for a 10^3 $M_\odot$ rotating ($a \cong m$) black hole in a typical interstellar ionized cloud ($\rho_\infty \sim 1$, $T_\infty \sim 1$ eV) we would expect a luminosity of γ rays $\sim 2 \times 10^{36}$ ergs sec^{-1}. Such luminosities would be consistent with the recently-identified γ-ray sources (Hermsen et al. 1977). Clearly the test for this mechanism would be the measurement of the spectrum at energies near 20 MeV to search for the predicted peak.

CONCLUSIONS

In summary, accretion of interstellar gas onto an isolated, rotating black hole could provide a high luminosity γ-ray source with a spectrum peaked near 20 MeV. Further calculations, including the density distribution of matter in the ergosphere, will be needed before the shape of the spectrum can be determined accurately.

ACKNOWLEDGMENT

I would like to thank Dr. Carl Fichtel and Dr. David Thompson of the γ-Ray Astronomy Group at Goddard Space Flight Center without whose support and encouragement this work would not have been successfully completed.

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