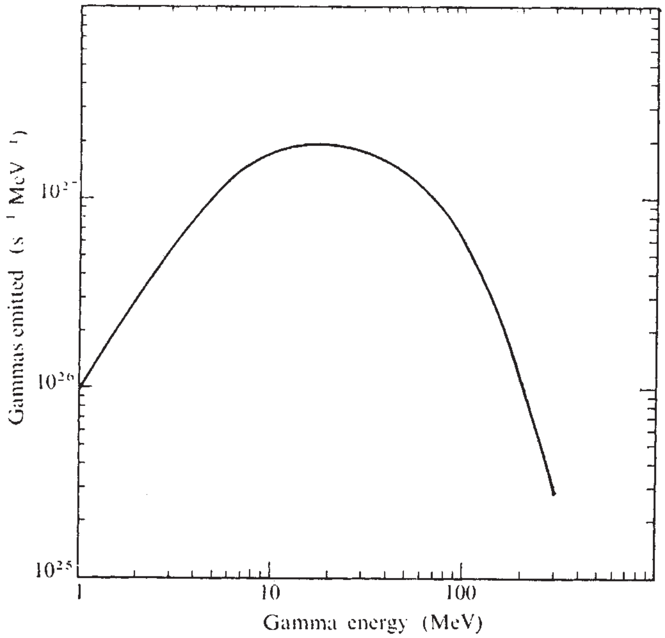

Fig. 2 Differential γ-ray spectrum from a 10 $M_\odot$ black hole in a region of density = 1 cm^{-3}, and θ_0 = 1eV.

of r. The total rate of emission of γ rays resulting from spherical accretion is:

$$\dot{N}\gamma = \int_{r_g}^{\infty} \langle\pi^0\rangle\, n^2\overline{\sigma v}\,(\theta)\;[1 + (\cos\psi - V/c)/(1 - V/c\cos\psi)]\; 2\pi r^2 \mathrm{d}r \qquad (6)$$

where V is the radial infall velocity and ψ is the half angle of the radiation 'escape cone'[3]. Numerical evaluation of the right side of equation (6), using the values of $\overline{\sigma v}$ (θ) shown in Fig. 1 and equation (3) and (4) gives:

$$\dot{N}\gamma \approx 3 \times 10^{26}\,(M/M_\odot)^3\,(1\text{ eV}/\theta_0)^3\,n_0^2\ \mathrm{s}^{-1} \qquad (7)$$

These γ rays have energies of the order of 20 MeV, so that the γ ray luminosity resulting from spherical accretion is:

$$L\gamma \approx 10^{22}\,(M/M_\odot)^3\,(1\text{ eV}/\theta_0)^3\,n_0^2\ \mathrm{erg\ s}^{-1} \qquad (8)$$

This is larger than the γ-ray luminosity resulting from bremsstrahlung emission[2], but it is small compared to the total luminosity of the black hole, which results from the synchrotron radiation of visible light[1]. It may be larger than indicated in equation (8) if matter is falling onto an isolated rotating black hole because of the accumulation of matter in orbits near r_g. Accreting disk models in binary systems[6], have a much lower luminosity γ-ray because the accreted material has time to radiate a significant fraction of its energy, thus invalidating the adiabatic approximation.

The spectrum of γ rays emerging from the accreting gas will be determined by: the energy spectrum of the π^0s as observed by a comoving observer; the Doppler shift resulting from the radial infall of the gas; and the gravitational redshift. More than half of the γ-ray emission comes from the region $r_g < r < 2r_g$, so the gravitational red shift is an important effect.

The γ-ray spectrum in a comoving frame which results from the energy spectrum of the π^0's, can be calculated to sufficient accuracy by noting that for laboratory energies of less than 4 GeV almost all pion production occurs through an N*(1236) intermediate state. Thus, in order to calculate the γ-ray spectrum in a comoving frame only the γ-ray spectrum in the rest frame of an N*(1236) need be known. It can be obtained[7] by convoluting the spectrum in the N* rest frame with the relativistic thermal Doppler spectrum $\phi(\omega) = (2\omega)^{-1}\gamma(\omega)\exp[(m_{N*}c^2/\theta_i)\ \gamma(\omega)]/K_1(m_{N*}c^2/\theta_i)$; where $\gamma(\omega) = (\omega/\omega_0 + \omega_0/\omega)/2$ and ω_0 is the γ-ray energy in the N* rest frame. If ω_1 is the γ-ray energy in the comoving frame then the frequency measured by a distant observer is:

$$\omega_{obs} = \omega_1\,[(1 - v/c)/\,(1 + v/c)]^{1/2}\,(1 - r_g/r)^{1/2} \qquad (9)$$

(We have neglected the angular dependence of the Doppler shift because the escape cone light of sight is nearly radial when the infall velocity is largest.) The spectrum obtained by integrating the contributions from all radii has a width of ~80 MeV, and falls off approximately as E^{-3} for 100 MeV $< E <$ 300 MeV (Fig. 2).

The spectrum (Fig. 2) is universal in the sense that its shape is independent of the mass of the black hole or the interstellar density. Thus, if many black holes are present in the Universe some kind of anomalous feature could be expected in the γ-ray background in the neighbourhood of 10 MeV. The spectrum from black holes in our Galaxy would have a peak at 18 MeV; the spectrum from black holes in other galaxies would peak below 18 MeV because of cosmological redshift which lowers the peak in the 'background' spectrum to ~ 10 MeV. An anomalous feature in the γ-ray background at about 10 MeV has, in fact, been reported at a level of about 10^{-4} γs cm^{-2} s^{-1} sr^{-1} MeV^{-1} (refs 8 and 9).

If this anomaly results from isotropic emission from external galaxies with 30 $M_\odot$ black holes, then about 10^{10} black holes per galaxy are required, assuming equation (7) for the γ-ray luminosity and n_0 = 100 cm^{-3}. As mentioned, higher γ-ray luminosities may occur, thereby decreasing the number of black holes required. In our Galaxy, upper limits on the emission above 15 MeV from the galactic centre[10] indicate that as many as 10^7 30 $M_\odot$ black holes may be in that vicinity if n_0 = 100 cm^{-3}.

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1 Schwartzman, V. F., *Soviet Astr.* AJ, **15**, 377 (1971).
2 Shapiro, S. L., *Astrophys. J.*, **180**, 531 (1973).
3 Zeldovich, Y. B., and Novikov, I. D., *Relativistic Astrophysics* (University of Chicago Press, Chicago, 1971).
4 Bondi, H., *Mon. Not. R. astr. Soc.*, **112**, 195 (1952).
5 Lock, W. O., and Measday, D. F., *Intermediate Energy Nuclear Physics* (Methuen, London, 1970).
6 Novikov, I., and Thorne, K. S., *Black Holes* (edit. by DeWitt, C., and DeWitt, B. S.), (Gordon and Breach, New York, 1973).
7 Stecker, F. W., *Cosmic Gamma Rays*, NASA SP-249 (Scientific and Technical Information Office, Washington DC, 1971).
8 Trombka, J. E., Metzger, A. E., Arnold, J. R., Matteson, J. L., Reedy, R. C., and Peterson, L. E., *Astrophys. J.*, **818**, 737 (1973).
9 Vedrenne, W., Albernhe, F., Martin, I., and Talon, R., *Astr. Astrophys.*, **15**, 50 (1971).
10 Share, G. H., Kinzer, R. L., and Seeman, N., *Astrophys. J.*, **187**, 54 (1974).

Do black holes really explode?

The creation of particles out of the vacuum will occur in regions of space–time where the metric is changing rapidly. Theoretical discussions of this process encounter some interpretational difficulties, however, because the concept of 'particle' is only well understood in Minkowski space. Nevertheless, in some simple cases, for example with the metric of homogeneous cosmologies, or of black holes of the Kerr and Schwarzschild type, the existence of a global timelike Killing vector allows a very plausible extension of the Minkowski space definition of particle. A number of exact results may then be proved. One of these results (ref. 1, and C. J. Isham and J. G. Taylor, personal communication) states that there is no creation of massless particles in the exterior region of a Schwarzschild black hole, which is the static end state reached as a result of spherically symmetric gravitational collapse. This result is not valid for a Kerr (rotating) black hole for essentially classical reasons[2].

Nevertheless, during the collapse of a spherically symmetric object, the metric near the surface will be changing rapidly on a time scale of $\tau \simeq 10^{-5} (M/M_\odot)$ s, so that on general grounds the production of massless particles with energy of order h/τ is expected. Many of these particles will escape from the surface of the object and reach distant observers. The energy removed in this way will slow up the collapse and may even prevent it completely, thus causing the collapsing object to 'explode' in a burst of radiation. Exact calculations of this explosion are not possible with present theory, which does not enable the back reaction of the particle creation on the metric (a quantum gravitational correction) to be evaluated. A rough idea may be obtained, however, by treating quantised fields in a given classical background metric, and estimating the amount of particle emission as the collapse proceeds.

If we assume that the production rate is more or less constant during the collapse, the surface will have a luminosity L_0, but a distant observer will see a rapidly fading luminosity as the retreating surface falls towards the event horizon:

$$L(t) = L_0 \exp(-t/\tau) \qquad (1)$$

Particle creation will only be important for objects with $M < < M_\odot$, and it follows from equation (1) that in this case the radiation will be emitted in a flash with a duration of much less than a microsecond. The spectrum of radiation will be given (roughly) by the Fourier transform of equation (1), that is, proportional to $\nu/(\nu^2 + \nu_0^2)$ where $\nu_0 = (2\pi\tau)^{-1}$. This is peaked around $\nu = \nu_0$ so that a distant observer might approximate this spectrum with that of a blackbody with a Planck spectrum $\nu/[\exp(h\nu/kT) - 1]$, corresponding to a temperature

$$T \simeq h\nu_0/k \simeq 10^{-6} (M/M_\odot) \text{ K} \qquad (2)$$

where k is Boltzmann's constant. This result has already been obtained in another way[3].

Treating the collapsing object as a blackbody radiator with temperature T for the duration of the 'flash', the energy emitted per unit time will be about $A\sigma T^4$, where σ is Stefan's constant, and A the surface area, which will not be greatly different from that of a final black hole of the same mass, that is, $16\pi G^2M^2/c^4$. Consequently, the total mass loss by the object as a result of massless particle emission will be in the region of

$$(16\pi M^2\sigma) \times (h\nu_0/k)^4 \simeq hc/MG \qquad (3)$$

with a numerical coefficient on the right hand side involving only small powers of 10. This result may be written as a fractional mass loss

$\Delta M/M \sim$ (Compton wavelength of object/Planck length)^2.

Evidently, black hole explosions with $\Delta M \simeq M$ will only occur for an object the Compton wavelength of which is comparable with the Planck length, that is for masses of about 10^{-4} g and densities of 10^{94} g cm^{-3}. This is just the region where quantum gravitational effects also become important. Indeed, this result is not surprising because in order to reverse the collapse, the back reaction of the created particles on the dynamics of the collapse needs to be appreciable, and this can only occur when quantum corrections to gravity become important.

Equation (3) is confirmed by the detailed calculations of Zel'dovich and Starobinskii[4], who have treated the problem of massless particle creation in the context of anisotropic cosmological models. They have verified the formula h/c^3t^4, originally deduced on dimensional grounds, for the energy density of created particles at a time t before collapse to a singularity. If a collapsing anisotropic single object is treated as a region of an anisotropic universe, this formula can be applied to obtain the total created particle energy-density over a time scale of order τ to obtain

$$(h/c^5)\tau^{-4} \times (\text{volume object}) \sim hc/MG$$

as before. Because of the additional tidal forces present in anisotropic collapse, spherically symmetric collapse would not be expected to lead to a greater particle production than this.

The conclusions of this simple treatment of particle production around collapsing objects seems to be in conflict with a recent result by Hawking[5], who claims that black holes as large as 10^9 gm would explode in massless radiation in about 0.1 s. Collapsing objects of this mass have an energy density only of the order 10^{-27} of that of quantum gravity fluctuations, so that this 'explosion' is more like a slow 'leak'. The e folding time for collapse is 10^{-29} s at this mass, so that Hawking's result implies that emission of massless particles continues to occur when the static limit of a Schwarzschild field is an exceedingly good approximation. It is not therefore clear what mechanism could be responsible for this emission (on the assumption of a reasonable definition of 'particle'). Any particles produced near the surface of a collapsing object will find it increasingly difficult to escape as the event horizon is approached. The last quantum ever able to reach a distant observer does so after an (asymptotic) time of only about 100 e folding times (10^{-27} s in this case)[6]. Hawking's result is, on the other hand, deduced on the assumption that the black-hole temperature given by equation (2) persists, unaffected by the collapse of the object, in the external asymptotic region, rather than fading out rapidly in accordance with equation (1). In our view it is a rather too literal interpretation of the concept of the 'temperature' of a black hole to apply it to emission processes in this way, and its use should be restricted to the discussion of absorption, as originally suggested by Bakenstein[7].

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1 Blum, B. S., thesis, Brandeis Univ. (1973).
2 Unruh, W., *Proc. R. Soc.* (in the press).
3 Bardeen, J. M., Carter, B., and Hawking, S. W., *Commun. math. Phys.*, **31**, 161–170 (1973).
4 Zel'dovich, Ya. B., and Starobinskii, A. A., *Soviet Phys. JETP*, **34**, 1159–1412 (1972).
5 Hawking, S. W., *Nature*, **248**, 30 (1974).
6 Misner, C. W., Thorne, K. S., and Wheeler, J. A., *Gravitation*, 873 (Freeman, San Francisco, 1973).
7 Beckenstein, J., *Phys. Rev.*, **D7**, 2333–2346 (1973).

Further simultaneous hard X-ray and optical observations of Sco X-1

THE optical and X-ray emissions from Sco X-1 are thought to come from a hot plasma as small as or smaller than a white dwarf[1], but the energy source and the time variations of the radiation are not understood.

In our 1971 observations we found a positive correlation between the optical luminosity and the intensity of hard X rays at the optically enhanced phase of Sco X-1 (refs 2 and 3). Although the optical enhancement seemed to be a flare, a rather poor time resolution of the photographic observation prevented us from identifying it for certain. During a balloon flight on April 16, 1972, an X-ray enhancement was observed simultaneously with an optical flare, the latter being verified by photoelectric observation. With the result of another balloon flight on April 19, 1972, the hard X-ray spectra at several different B magnitudes are available for the study of the correlation between X-ray and optical emissions.

The instruments essentially the same as the one in the previous flight[3], were launched onA pril 16 and 19, 1972, from Hyderabad, India. The balloon floated at the atmospheric depth of 2.9 to 3.0 g cm^{-2} for about 4 h in each case. One of the counters in the April 16 flight malfunctioned, and its data were discarded.