letters

Upper limits for γ-ray bursts from primordial black holes

PAGE AND HAWKING[1] have predicted that primordial black holes of mass $\sim 10^{15}$ g will evaporate, reaching an explosive stage at a mass which depends on the nuclear processes occurring. For the composite particle model 10^{34} erg of γ rays will be produced at energies of 100–1,000 Mev. For the elementary particle model 10^{30} γ rays of energy 5×10^{12} eV are expected. We have already set upper limits[2,3] for the rate of primordial black hole explosions in the Galaxy assuming the composite particle model. We report here upper limits from two other sets of data, assuming the elementary particle model and using the atmospheric Cerenkov technique as before.

In the first data set the Mt Hopkins 10-m reflector[4] was used with a field of view of 1°. Approximately 112 h of observation were analysed. As the detector has an energy threshold of 10^{11} eV it will respond to 5×10^{12} eV primaries over a large area. Events were recorded on analogue magnetic tapes together with a standard frequency and time markers. They were analysed by reconstituting the standard frequency with a phase-locked loop, and after scaling, deriving a 0.1 s clock signal. The number of events recorded in each successive 0.1 s interval was determined with a mini-computer and a distribution derived. The characteristic signature of a γ-ray burst would be a group of individual showers occurring together within 0.1 s.

At five points in the data bursts were observed which were incompatible with random Poisson expectation. Four of these were very large and had durations of 2–11 s. They were probably local in character and due to man-made interference. The fifth event was just above the burst threshold (12 showers) and lasted 0.1 s. Without a distant coincident detector this event could not be ascribed to a cosmic origin. We therefore derived an upper limit at the 99% confidence level of 6.1 events in 112 h, or 477 events yr^{-1}.

The collection area of showers of 5×10^{12} eV was estimated at 5×10^{9} cm^2 and the solid angle was taken conservatively at the geometric value of 2.4×10^{-4} sr. Twelve showers were required for a detectable burst, corresponding to 96 erg and giving a sensitivity of 1.9×10^{-8} erg cm^{-2}. The maximum detectable distance r is then given by $4\pi r^2 = 8\times10^{30}/1.9\times10^{-8}$ cm^2, hence $r = 5.7\times10^{18}$ cm = 1.9 pc. The sensitive volume $V=\Omega r^3/3 = 5.5\times10^{-4}$ pc^3. The upper limit for the explosion rate is then 8.7×10^{5} explosions pc^{-3} yr^{-1}.

In the second data set[5] two 1.5-m reflectors were used in coincidence aligned parallel to each other at varying zenith angles. The full field of view was 5°; 78 h of observation were obtained. The normal counting rate was about 300 showers min^{-1} at the zenith. The energy threshold for the system was 3×10^{12} eV and the collection area for 5×10^{12} eV γ-rays estimated at 3×10^{9} cm^2. Events were recorded on analogue magnetic tape as before.

No groups of events were recorded beyond Poisson expectation. Seven events would be required for a statistically detectable burst, corresponding at 5×10^{12} eV to 56 erg and giving a sensitivity of 1.8×10^{-8} erg cm^{-2}. The maximum detectable distance r is then given by $4\pi r^2 = 8\times10^{30}/1.8\times10^{-8}$ cm^2 hence $r=5.9\times10^{18}$ cm = 2.0 pc. The sensitive volume $V=\Omega r^3/3 = 1.6\times10^{-2}$ pc^3. The upper limit at the 99% confidence level for zero bursts observed is 4.3 bursts in 78 h or 483 yr^{-1}. The upper limit for the explosion rate is then 3.0×10^{4} explosions pc^{-3} yr^{-1}.

Using particle detectors at sea level with a higher energy threshold, which required some assumptions about the primordial black hole emission spectrum, Fegan *et al.*[6] have found lower limits than those reported here. A further improvement in the Cerenkov method would require the use of one or more detectors with considerably larger collection area, and if possible, a wider field of view. A limit of about 1 explosion pc^{-3} yr^{-1} is set irrespective of the nuclear model assumed, by observations of the isotropic γ-ray spectrum[1]. While the limit set with the Cerenkov technique assuming the composite particle model is only 4×10^{-2} explosions pc^{-3} yr^{-1} (ref. 3), it seems likely that Cerenkov, particle, or satellite γ-ray detectors will probably not produce limits lower than about 10^3 explosions pc^{-3} yr^{-1} when the elementary particle model is assumed.

We thank E. Horine for observational help, and the National Science Council of Ireland and the Smithsonian Research Foundation for partial support.

N. A. PORTER

Physics Department,
University College,
Dublin 4, Ireland

T. C. WEEKES

Harvard-Smithsonian Center for Astrophysics,
Mt Hopkins Observatory,
Amado, Arizona 85640

Received 23 October; accepted 24 November 1978.

1. Page, D. N. & Hawking, S. W. *Astrophys. J.* **206**, 1 (1976).
2. Porter, N. A. & Weekes, T. C. *Astrophys. J.* **212**, 224 (1977).
3. Porter, N. A. & Weekes, T. C. *Mon. Not. R. astr. Soc.* **183**, 205 (1978).
4. Helmken, H. F. Fazio, G. G., O'Mongain, E. & Weekes, T. C. *Astrophys. J.* **184**, 245 (1973).
5. Porter, N. A., Delaney, T., Helmken, H. F. & Weekes, T. C. *Nuovo Cimento* **32B**, 514 (1976).
6. Fegan, D. J., McBreen, B., O'Brien, D. & O'Sullivan, C. *Nature* **271**, 731 (1978).

A non-singular quantum Universe

CLASSICAL relativistic singularities remain one of the most puzzling problems of contemporary physics. Although no consensus of opinion has been attained on their status, a great deal of work has been devoted to the search for physical mechanisms capable of eliminating the cosmological singularities, whose existence follows from the theorems of Hawking and Penrose[1,2]. The alternative view that the initial singularity of big-bang models is essential for the coming into being of the Universe, has also been advocated[3,4]. Some suggestions of cosmological singularity avoidance have recently come to light, in the 'classical' quantum regime (from 10^{-43}–10^{-23} s) (refs 5–8) or even without resorting to quantum effects[9]. The quantum gravitational period ($t<10^{-43}$ s) remains potentially very interesting for searching for singularity avoidance mechanisms. An interesting approach is that of quantum cosmology, based on the hamiltonian formulation of general relativity (Dirac's[10] or Arnowitt, Deser and Misner's[11] (ADM) method). This approach was initiated by De Witt[12] and then followed by Misner[13] and many others (see refs 14,15) and is used here to derive a non-singular quantum cosmological model.

0028–0836/79/0277—0199$01.00