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# The atmospheric Cherenkov technique in searches for exploding primordial black holes

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The Cherenkov technique has been used with a number of detectors, ranging from 1.5 $\mathrm{m^2}$ mirrors to the Central Receiver Test Facility of 8400 $\mathrm{m^2}$. Limits have been set to the flux of primordial black holes for various models of the evaporation process.

Page & Hawking (1976) have suggested that black holes of mass in the region of $10^{15}$ g will evaporate in a time of the order of the age of the Universe, and that the final stages of evaporation will be very rapid. Such black holes, if they exist, must be primordial, since only in the early Universe could conditions necessary for their production occur. The mass at which the evaporation becomes explosive, and the duration of the final stage, depend on unknown nuclear characteristics. Two extreme models are considered by Page & Hawking: an elementary particle model, in which about $10^{30}$ erg§ of $\gamma$-rays at $5 \times 10^{12}$ eV are released in the final 0.1 s, and a composite particle model in which, following the statistical bootstrap formulation of Hagedorn (1965), about $10^{35}$ erg are released in the final $10^{-7}$ s. In the composite particle model about 10% of the total energy appears as $\gamma$-rays of energy 100–1000 MeV. Upper limits can be deduced for the rate at which black holes are evaporating in the Universe, by measuring the diffuse $\gamma$-ray component. The rate of explosions in our Galaxy is expected to be higher by a factor of $10^6$ because of clustering. Page & Hawking deduce an upper limit of about 1 explosion $\mathrm{pc^{-3}\,a^{-1}}$ from measurements of the diffuse radiation.

Direct observation by Belyaevskii *et al.* (1975) with a $\gamma$-ray detector on the Cosmos 561 satellite leads to an upper limit of about 78 explosions $\mathrm{pc^{-3}\,a^{-1}}$, and Share *et al.* (1977), with a balloon-borne system, find an upper limit of $9 \times 10^3\ \mathrm{pc^{-3}\,a^{-1}}$, with a lower energy limit of 15 MeV. Direct detection of bursts with satellite or balloon-borne systems does not yet therefore compete with the upper limit deduced from the background radiation.

An improvement in the upper limits may however be set by the use of the atmospheric Cherenkov technique, where the detection area is of order $10^5\ \mathrm{m^2}$. Coincident detectors must be used at separations greater than the diameter of the Cherenkov light pool from an individual shower. In practice separations of hundreds of kilometres are desirable, to rule out not only showers but also lightning or artificial interference as a source of coincidences. Accurate timing at each station, or a direct link, is required to establish coincidences.

Upper limits have been reported (Porter & Weekes 1978) with use of the Cherenkov technique, with detectors of area 70–80 $\mathrm{m^2}$ separated by 400 km. Assuming the composite particle model, a limit of 0.04 $\mathrm{pc^{-3}\,a^{-1}}$ was obtained. The limit found assuming the elementary particle

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§ 1 erg $= 10^{-7}$ J.

model was much higher, at $3.0 \times 10^4$ pc$^{-3}$ a$^{-1}$ (Porter & Weekes 1979), and for this model lower values can be obtained by using particle detectors at sea level or mountain altitudes (Fegan *et al.* 1978; Bhat *et al.* 1980).

Further progress requires larger detectors, with high capital costs. There are, however, a number of solar furnaces in existence or under construction with possible applications in this field. Indeed, one of the detectors used by Porter & Weekes (1978) was the White Sands 9 m × 9 m solar furnace. Preliminary work has been made with the Sandia Laboratories Central Receiver Test Facility (C.R.T.F.) at Albuquerque, New Mexico. This has, at 8250 m$^2$, a sensitive area two orders of magnitude larger than any optical device so far used in astronomy. It consists of 222 heliostats, each of area 37 m$^2$ and individually driven so as to focus an image of the Sun on a point at the top of a single high tower. The main problems in applying this to the Cherenkov technique arise from the size of the focal spot. For a typical Cherenkov image this would be 4 m in diameter. In addition to the need for a large collection area at the focus, a large field of view (half-field about 40°) is required for efficient light collection.

TABLE 1. LARGE SOLAR ARRAYS

| Facility | 10 metre | J.P.L. | White Sands | White Sands | Georgia Tech | C.N.R.S. | Sandia C.R.T.F. |
|---|---|---|---|---|---|---|---|
| Location | Mt Hopkins, Arizona | Edwards A.F.B., California | W.S.M.R.†, New Mexico | north end of W.S.M.R. | Atlanta | Odeillo, France | Albuquerque, New Mexico |
| Configuration | tracking dish | tracking dish | horizontal furnace | parabolic reflector | central receiver | vertical and horizontal furnace | central receiver |
| Collection area/m$^2$ | 75 | 95 | 132 | 500 | 532 | 2835 | 8250 |
| Tracking capability | yes | yes | no | yes | yes | yes | yes |
| Time spread/s | $6 \times 10^{-9}$ | $6 \times 10^{-9}$ | $6 \times 10^{-9}$ | 0 | $10^{-7}$ | $5 \times 10^{-7}$ | $10^{-6}$ |
| Environment | dark | military base | military base near roads | dark site | university campus | centre of village | military base |
| No. of steerable elements | 1 | 1 | 1 | 1 | 550 | 63 | 222 |

† White Sands Missile Range.

We have tested three methods of concentrating the light further:

(*a*) *Light cones*. Seven of these, made from aluminized Mylar, were placed at the focus of the facility. The angle of taper was 21.4°, and the input to output area ratio was 9, fitting 12.5 cm photomultipliers at the narrower ends. The area covered by the cones was therefore 6300 cm$^2$, about 4% of the total required. A shower spectrum was seen, and star transits were made successfully. It would appear that if total coverage of the field were achieved, requiring about 180 photomultipliers, the system would be an effective detector.

(*b*) *Fluorescent detectors*. These consist of rectangular sheets of plastic loaded with a fluorescent chemical which absorbs in the blue and emits in the green-yellow. About 75% of the re-emitted light is trapped by total internal reflexion and propagated to the edge, where it can be collected by a light guide coupled to a photomultiplier. Tests have been made with these materials but the response has been disappointing. It was found later that the plastic had undergone some poisoning.

(*c*) *Searchlight mirrors*. One of these, with diameter 1.5 m and $f/0.4$ aperture ratio, was placed at the focus of the array, concentrating on to five 12.5 cm photomultipliers. Again a shower spectrum was seen, but the efficiency was reduced by heavy coma. The effective full field of view was only about 20° so that many of the heliostats were not viewed at all. This is a general disadvantage with this method.

Generally it is clear that to take advantage of the very large collecting area it will be necessary to scale up the experiment considerably. There are, however, several smaller systems completed or under construction. These are described in table 1. A combination of two or more of these could produce limits considerably lower than those already found. Two mirrors, each of 25 m diameter, or 500 $m^2$ area, for instance, could give a limit of 0.004 events $pc^{-3}\ a^{-1}$, in 50 hours of observation.

Some objections to the Hawking theory of evaporation have been raised recently by Tipler (1980). He concludes that either black holes will evaporate rapidly, so that very few can now exist, or that the evaporation process must be quite different from that currently supposed.

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