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# EXPERIMENTAL TESTS OF THE SUPERNOVAE ORIGIN OF COSMIC RAYS

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## ABSTRACT

The general problem of supernovae explosions as a possible origin of cosmic rays is reviewed. The shock wave theory of Colgate et al., the only detailed model of supernovae explosions to date, predicts a short, intense high energy gamma-ray pulse associated with the explosion and cosmic ray acceleration. Two experimental tests capable of detecting the predicted initial explosion are suggested. One is a spark-chamber gamma-ray telescope which, when flown above the earth's atmosphere, could detect pulses of protons above 30 mev. The other experiment, which is ground-based, could detect the fluorescence produced in the atmosphere by the electromagnetic pulse radiated by the supernova during its explosion.

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# EXPERIMENTAL TESTS OF THE SUPERNOVAE ORIGIN OF COSMIC RAYS

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## INTRODUCTION

Although the existence of cosmic rays has been known for many decades, the origin of these particles is still uncertain. At present, there are two general theories. One is that cosmic rays for the most part have their origin in the galaxy and most likely originate in supernova bursts—a concept extensively treated by Ginzburg and Syrovatskii (1964), and others. The other theory is that cosmic radiation pervades the universe, or at least a local supercluster of galaxies at about the level observed near the solar system and possibly originates in quasi-stellar objects—an idea recently discussed by Burbidge and Hoyle (1964) and Burbidge and Burbidge (1965). Although extensive and thorough theoretical work has been done, there have been few experimental measurements that shed light on this important question. This lack is largely due to the problem of relating the cosmic rays back to their source after they have passed through interstellar matter and been deflected innumerable times by the interstellar magnetic fields.

At present, observations indicate that supernovae are the most energetic discrete sources in our galaxy and other normal galaxies, having estimated total energy outputs of $10^{49}$ to $10^{52}$ ergs (Ginzburg and Syrovatskii, 1964; Minkowski, 1964; Shklovskii, 1950). Although exceptional objects such as radio galaxies and possibly quasars seem to have energies of $10^{60}$ ergs associated with them, by far the most catastrophic events in a normal galaxy are supernovae. Recently, Colgate (1967b) has shown that it may be possible to explain quasi-stellar sources in terms of a multiple-supernovae model; so, even in the case of the metagalactic model for cosmic rays, supernovae could be the source of the cosmic radiation.

Although it was known for some time that supernovae were powerful optical emitters, it was the radio-astronomy data of the last few decades and their interpretation in terms of synchrotron radiation from high-energy electrons that gave the strongest initial support to the supernovae theory of the origin of cosmic rays. There are several ways in which particles might be accelerated to cosmic-ray energies in supernovae (Ginzburg and Syrovatskii, 1967). One of the most attractive is the hydrodynamic-shock theory suggested originally by Colgate and Johnson (1960),

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wherein the cosmic rays originate in the shock ejection of the outer layers of the supernova. In this picture, a gravitationally collapsing stellar core emits a large flux of neutrinos whose mean free path becomes short compared to the dimensions of the star as its temperature and density become sufficiently high. In this way energy is transferred to the outer layers, resulting in the ejection of a certain fraction of the stellar mass at relativistic speeds as cosmic rays.

One consequence of the hydromagnetic supernovae-origin theory is that a definite prediction is made regarding an energetic electromagnetic pulse being emitted from the surface layer during this layer's ejection and subsequent adiabatic expansion (Colgate and White, 1966).

The detection of such a pulse and identification of it with an optically observed supernova is clearly an important test of a very plausible supernovae theory of the origin of cosmic rays. Therefore, it is worth exploring the ways such a pulse might be detected.

The purpose of this article, aside from reaffirming the physical significance of this photon pulse and the value of looking for it, is to discuss experimental ways by which such a pulse could be detected and its properties measured.

## THE SUPERNOVA EXPLOSION

### Theoretical Considerations

Burbidge, Burbidge, Fowler, and Hoyle (1957) were the first to suggest that a supernova explosion is initiated by the dynamical implosion of a massive star resulting from its gravitational instability at the end of its evolution. They further suggested that the subsequent explosion was thermonuclear in origin. This approach was pursued further by Hoyle and Fowler (1960) and by Ono et al. (1960, 1961) and Ohyama (1963). Colgate and White (1966), however, have shown that dynamical effects of the rarefaction wave created by the implosion will predominate over the thermodynamic effect and, regardless of the details of the instability, the entire star will receive the gravitational energy freed in the core region in a time short as compared to the tranversal time of sound. Similar numerical hydrodynamic calculations have also been carried out by Arnett (1966, 1967), who, in general, agrees with these conclusions.

In this latter theory, as we have mentioned in the introduction, neutrinos are emitted from the core region as the imploding matter falls into it. The deposition of the neutrino energy in the outer layers of the star then gives rise to a radially outgoing shock wave. The velocity and internal energy received by each layer increases toward the surface until the velocities in the outer envelope become highly relativistic, leading to the ejection of cosmic rays. Although a number of authors have indicated the plausibility of creating cosmic rays in this manner (Minkowski, 1964 and Shklovskii, 1950) the only specific calculations known to the present authors are due to Colgate and White (1966).

In the theory just described, it is essential that the kinetic energy of the matter falling on the dense nuclear core be transferred rapidly to the outer parts of the star, thereby ensuring a violent mass ejection in the form of cosmic rays. In a recent reanalysis of the supernova problem including a study of the equation of state and the energy transfer rates, Arnett (1967) concludes that this violent ejection can occur only if $M_{core} \lesssim 2M_0$. In the range above $4M_0$ there is no mass ejection, and between these values the mass ejection will not be violent. On the other hand Colgate and White (1966) have concluded that similar calculations still allow relativistic mass ejection in pre-supernova stars of around 50 $M_0$. Applying their results to a 10-$M_0$ pre-nova star, they have shown that after the explosion a $10^{-4}$ mass fraction of the star will be accelerated to a velocity above $2.6 \times 10^{10}$ cm/sec in a fraction of a second after the onset of collapse. This ejected mass fraction is identified with cosmic rays; using similarity solutions, they predict an energy spectrum that agrees with the observed cosmic-ray spectrum (Colgate and Johnson, 1960; Colgate and White, 1963). They also show that with the observed frequency of supernovae and the calculated cosmic-ray energy produced by supernova, $\sim 10^{51}$ ergs, the cosmic-ray energy density observed locally can easily be explained. To associate the cosmic-ray particles directly with a source experimentally, a neutral and long-lived component must be used, since the charged cosmic-ray particles suffer an unknown number of deflections and spirals in the complicated magnetic fields of the intervening space.

With this in mind, Colgate (1967a) has predicted the photon flux from a 10 $M_0$ supernova on the basis of his model. The results indicate that approximately $5 \times 10^{47}$ ergs could be produced per decade of energy interval up to a few Bev. The time of emission is around tens of microseconds at high energies and proportionally longer at lower energies.

There are still many uncertainties in the mathematical treatment of the problem, arising partly from a lack of experimental evidence from which to formulate a theory that may be applied on a supernova scale. Thus many questions relating to supernovae are still unanswered. A critical test of the association of the origin of cosmic rays with the explosive phase of a supernova clearly is the emission of a very short high-energy electromagnetic pulse at the expected intensity by the supernovae.

## Experimental Data on Early Stages of Supernovae

Although supernovae remnants have been observed in the x-ray, optical, and radio parts of the electromagnetic spectrum, the detection of a supernova in its initial stage of explosion has been limited to the optical band only. The optical observations to date have not been designed to observe pulses of short duration; therefore, they cannot record pulses with time scales shorter than the exposure times of the photographic plates (which are of the order of many minutes). Table 1, extracted from Minkowski (1964), Colgate and White (1966), and Morrison and Sartori (1966), lists the average properties of the two main types of supernova observed in the optical band.

Besides giving the average properties of the supernovae explosions, the optical data also provide information on the frequency of occurrence of these events. To date, there have been over 200 recorded extragalactic supernovae. Zwicky (1967) estimates that on the average there is one supernova per galaxy per 350 years. However, considerations of efficiency of detection

Table 1

Characteristics of Supernovae Explosions as Deduced from Optical Observations.

| Type | Total Optical Energy (ergs) | Peak Luminosity (ergs/sec) | Ejected Hydrogen | Ejected Mass ($M_0$) | Observed Kinetic Energy (ergs) | Occurrence | Light Curve | Spectral Features |
|---|---|---|---|---|---|---|---|---|
| I | $4 \times 10^{49}$ | $10^{43}$ | No | 0.1 - 1 | $4 \times 10^{48-49}$ | Old Stars | Rise-time few days. After maximum, drops 2 to 3 mag. in 20-30 days, then decays exponentially with time scale of 40 to 80 days. | Broad features that could represent emission and/or absorption |
| II | $2 \times 10^{49}$ | $10^{43}$ | Yes | 1 - 10 | $4 \times 10^{50-51}$ | Young Stars | Rise-time few days. After maximum, drops 1.5 mag. in 20-30 days, then decays much faster than Type I | Considerable individual variations. Near maximum, spectrum is continuous. Emission lines develop later. |

as a function of distance have modified the frequency estimate to as high as one supernova per galaxy per 50 years (Katgert and Oort, 1967). Furthermore, the concentration of the known supernovae remnants in our own galaxy favors a frequency around 1 supernova per 50 years (Shklovskii, 1950).

## EXPERIMENTAL APPROACH

In this section we shall discuss two experiments that could detect a rapid pulse of photons emitted by a supernova explosion. One experiment is a spark-chamber gamma-ray telescope that would detect pulses of photons above 30 Mev when flown above the earth's atmosphere; the other is a ground-based experiment that could detect the fluorescence produced in the atmosphere by any form of electromagnetic pulse of radiation from ultraviolet to hard gamma rays.

### Gamma-Ray Detector

Spark chambers have already been used extensively in the search for discrete sources of high-energy celestial gamma rays (Cobb et al., 1965; Frye and Smith, 1966; Helmken and Fazio, 1966; Fichtel et al, 1967; Ogelman et al., 1966). This instrument has the unique advantages of good angular resolution, large area, wide aperture, and pictorial representation of a gamma ray which greatly aids the rejection of various false events. Furthermore, the data can be conveniently digitized, eliminating the need of recovery, as is necessary with nuclear emulsions or photographic film.

When a spark chamber is incorporated in a gamma-ray telescope, thin conversion plates are normally interleaved between chamber modules in order to convert the gamma ray into an electron-positron pair with a minimum loss in directional information, and at the same time measure its energy from the multiple Coulomb scattering of the electrons in the plates.

Figure 1 shows a typical gamma-ray telescope using a spark chamber system. The A counter, normally a plastic scintillator, is used as an anticoincidence device to reject charged particles. Scintillator counter B and Cerenkov counter C are used in coincidence to define the geometry and discriminate against upward-moving particles. The combination of a pulse from B and C with none from A gives the signature of a downward-moving charged particle resulting from a neutral primary; the spark chamber is then triggered, yielding a three-dimensional "picture" of the event.

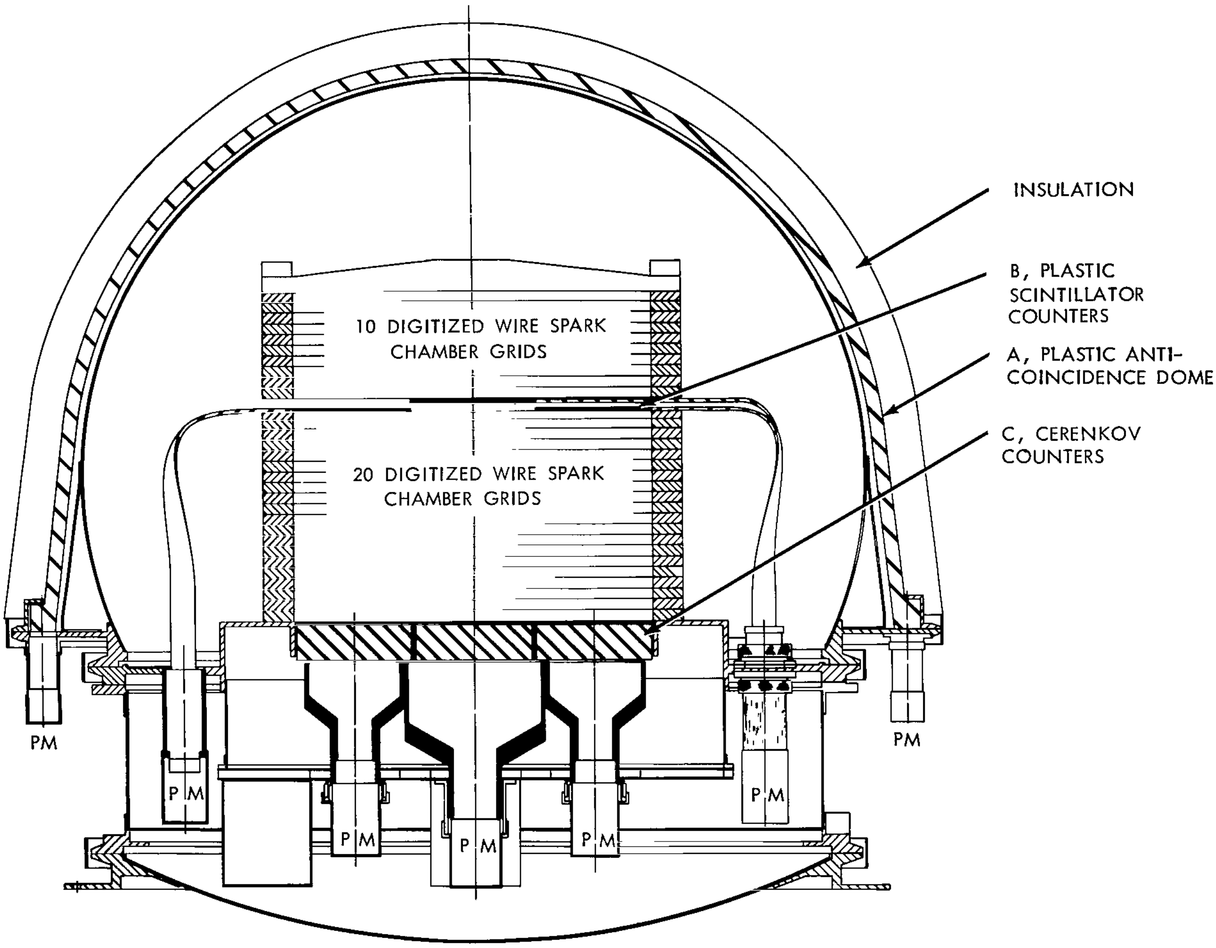



Figure 1—Schematic cross section of the 1/2 m x 1/2 m digitized spark-chamber gamma-ray telescope under construction at Goddard Space Flight Center.

Such a system (which is basically designed to observe a low flux of gamma-rays), if operated in its normal manner, would be very inefficient in detecting a short, intense gamma-ray pulse from a supernova for two reasons. First, in an intense gamma-ray pulse, some of the photons will convert in the anticoincidence dome and in the atmosphere above, giving rise to electrons that will trigger the A counter, thereby rejecting the event. Second, in trying to reduce the accidential coincidence rates, the typical coincidence times have been reduced to the order of one microsecond or less. In some experiments, in order to minimize the resparking of old tracks, the sensitive times of the spark chambers have been reduced to similar amounts by the use of clearing fields. However, with a slight modification, such a system can be converted into a supernova-type gamma-ray burst detector. The omission of the anticoincidence requirement removes the problem of the rejection of the event by the A detector. Rejection of the great majority of the charged-particle background events can be accomplished by raising the coincidence triggering requirement between the B and C counters from one particle to several within a short period. By raising the coincidence gate width to the maximum sensitive time of the spark chambers (which is of the order of 5 to 10 microseconds with good gas mixtures and no clearing fields), the time interval over which gamma rays are collected can be increased; hence, the probability of detecting a weak pulse. In the next paragraphs, the detection of a gamma-ray pulse in such a detector will be examined in more detail.

If a supernova at a distance R generated a photon pulse of duration $\tau_{SN}$, total energy W within an energy interval centered around $E_\gamma$, then the flux of gamma-ray photons reaching the top of the atmosphere would be

$$S = \frac{W}{4\pi R^2 E_\gamma} \text{ photons/cm}^2\text{-pulse} \tag{1}$$

Taking the sensitive time of the apparatus as $\tau_A$, efficiency of detection as $\epsilon$, and the area as A, we obtain

$$\left(\frac{W}{4\pi R^2 E_\gamma}\right)\left(\frac{\tau_A}{\tau_{SN}}\right)\epsilon A \tag{2}$$

detected pairs in the spark chamber per supernova. Using $W \simeq 5 \times 10^{47}$ ergs per decade and $\tau_{SN} \sim 1.5 \times 10^{-5}$ sec (as suggested by Colgate, 1967a), using typical telescope parameters $\epsilon \sim 0.2$, $\tau_A \sim 5 \times 10^{-6}$ sec, $A = 10^3$ cm$^2$, $E_\gamma = 50$ Mev, $E_{max}/E_{min} \approx 10$, and requiring that we have more than three pairs in the chamber—all this implies that the radius R out to which such supernovae may be detected is:

$$R < 10^{26} \text{ cm} .$$

Assuming an average density of $5 \times 10^{-75}$ galaxies/cm$^3$ gives $2 \times 10^4$ galaxies within this radius. If we assume that frequency of supernovae is one per galaxy per 50 years, and that the gamma-ray telescope has a solid angle for detection of 1 steradian, this detector then could observe about one supernova burst per 10 days. Such an apparatus would have a 5-percent probability of observing a supernova on a balloon flight. On a satellite flight, the exposure time is multiplied by 1,000; thus 50 or so such pulses should then be recorded.

The approximate background counting rate of such a telescope due to charged cosmic rays can also be estimated. If we require two or more particles to be in an area A within time $\tau_A$ this would be approximately

$$(JA\Omega)^2 \tau_A \tag{3}$$

where J is the cosmic-ray flux and $A\Omega$ is the area-solid-angle product for the apparatus. Taking J to be about 0.1 $cm^2$ per sec sr and $A \sim 10^3$ $cm^2$ per sr gives about 3 counts per minute as the background. It is essentially impossible that two or more cosmic-ray tracks would be mistaken for a supernova-type gamma-ray burst by coming from the same direction and displaying photon characteristics.

In view of the very small increase in dead time introduced by incorporating a gamma-ray pulse mode into a conventional gamma-ray spark-chamber telescope, it is quite feasible to fly a single detector system which can be operated in both the conventional gamma-ray and supernovae modes by adding a relatively small amount of electronic logic circuitry. With these considerations in mind, two different gamma-ray telescopes that are under construction at Goddard Space Flight Center will be examined.

*Gamma-Ray Explorer*

Figure 2 shows the basic structure of the digitized-wire spark-chamber telescope proposed by Fichtel, Kniffen, and Ögelman, to be flown on the SAS-B Satellite scheduled for launch in the first half of 1971. In general the apparatus is quite similar to the type of gamma-ray detector just discussed, with the exception of having the B and C counters composed of four segments of equal area (each about 150 $cm^2$) that in the normal gamma-ray counter mode are used in B-C pairs as telescopes, to avoid events with large zenith angles. To include a supernova pulse-detecting mode in this telescope, a second triggering system will be added. The mode disregards the A counter, but demands that pulses corresponding to particles of minimum ionization or greater occur in two of the B segments and three of the C segments within five microseconds. The decision to require two B and three C pulses is based on a desire to keep the number of triggers resulting from the charged particle background down to a level where these events take up only a negligible percentage of the exposure time. This type of geometrical selection in tiles, of simultaneously arriving events is simpler than trying to pulse-height-analyze the analog signals in a large counter and is well worth the slight loss of efficiency due to particles traversing the same tile.

Figure 3 is a graph of the triggering probability as a function of the average flux of high-energy gamma rays normal to the apparatus for triggering modes of 1B + 2C, 1B + 3C and 2B + 3C. In Figure 4 is a list of background event rates for these modes and a sketch of the dominant type

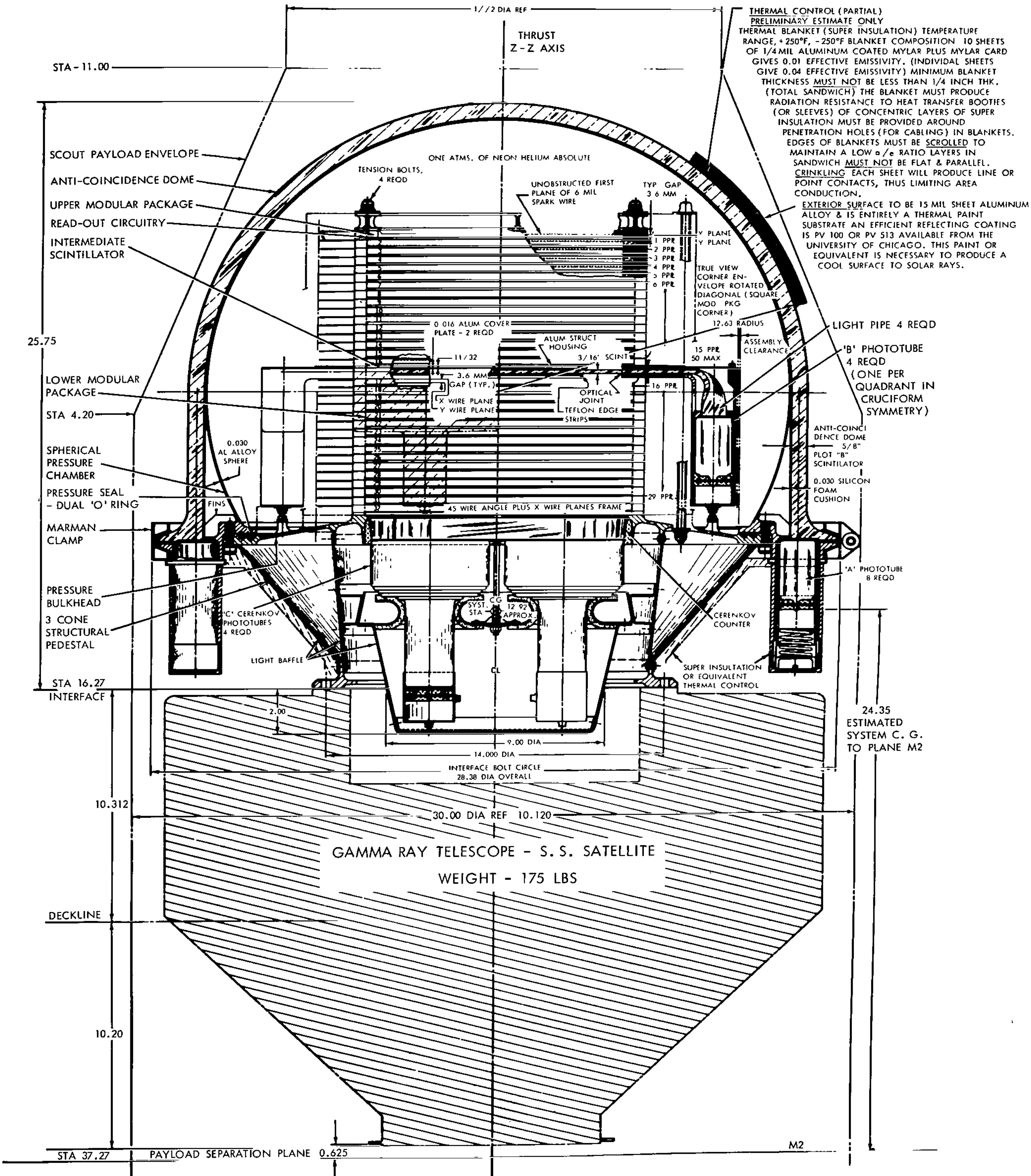



Figure 2—The proposed SAS-B gamma-ray telescope. The two 10 in. x 10 in. area spark chamber units each consist of wire grid modules with 1/50 radiation length pair-producing plates between wire planes. The chambers are surrounded by an anticoincidence counter as shield, and are triggered by coincidence between vertical elements of the central scintillator and Cerenkov counter assemblies. The vehicle below contains the electronics, telemetry, data handling and orientation systems.

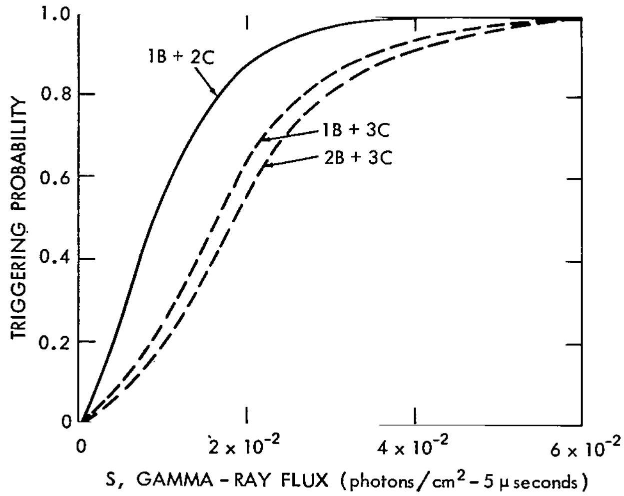



Figure 3—Triggering probability versus the average flux of high-energy gamma rays normal to the surface within the gate width 5 microseconds for various modes of triggering the proposed SAS-B gamma-ray telescope.

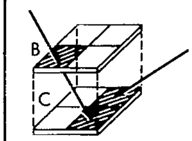
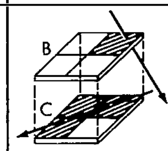
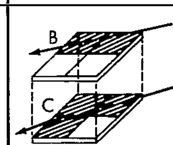
| TRIGGERING CRITERIA | BACKGROUND (COUNTS/MIN) | DOMINANT GEOMETRY |
|---|---|---|
| 1B + 2C | 4.0 |  |
| 1B + 3C | 0.4 |  |
| 2B + 3C | $10^{-3}$ |  |

Figure 4—Background trigger rates within 5-microsecond gates, and dominant background geometry, for various criteria of triggering the proposed SAS-B gamma-ray telescope in the supernova mode.

of background triggering geometry of the cosmic rays. Because of the finite thickness of the B and C counters, cosmic rays that pass sideways through the counters seem to provide most of the background in the 1B + 3C and 2B + 3C modes. In view of the fact that the gamma-ray flux for a triggering probability of 50 percent only increases from $0.9 \times 10^{-2}$ photons/cm$^2$ per 5$\mu$secs to $1.6 \times 10^{-2}$ photons/cm$^2$ per 5$\mu$secs from the 1B + 3C mode to the 2B + 3C mode, while the background decreases from 0.4 counts/min to $10^{-3}$ counts/min, it is clearly advantageous to use the 2B + 3C mode to avoid any significant increase in the dead time.

The expected recording rate in orbit per unit solid angle and unit time is given by

$$I = f \int_0^\infty \rho_g P(R) R^2 dR , \tag{4}$$

where f is frequency of supernovae per galaxy, $\rho_g$ is the density of galaxies, R is the radius vector, and P(R) is the probability that a supernova at a distance R will trigger the apparatus. With the values of the supernova parameters used in the previous discussions ($W \sim 5 \times 10^{47}$ ergs, $E_\gamma \sim 50$ Mev, $\tau_{SN} \sim 1.5 \times 10^{-5}$ sec, $\rho \sim 5 \times 10^{-75}$ galaxies/cm$^3$, f $\sim$ 1 supernova per galaxy per 50 years), this rate is $10^{-6}$ supernovae pulses/sec-sr. In one day, the telescope scans $10^5$ sr-seconds; therefore, 0.1 supernova/day (or about 40 supernovae/year) should be observed by this apparatus if the theory is correct.

*1/2 M × 1/2 M Spark-Chamber Gamma-Ray Telescope*

Construction of a 1/2 M × 1/2 M digitized spark-chamber gamma-ray telescope is already in process at Goddard Space Flight Center. Figure 1 is a schematic diagram of the system. Except for the size and the fact that the coincidence telescope is divided into nine equal segments ($\sim$260 $cm^2$ each) instead of four, this apparatus is quite similar to the one described in the preceding subsection, "Gamma-Ray Explorer". Considerations in line with those previously discussed seem to favor a triggering mode of 2B + 3C for this detector system also. The triggering probability for an incident flux of $6 \times 10^{-3}$ photons/$cm^2$-5$\mu$secs. is about 50 percent. The background rate is about $10^{-1}$ counts/minute. Calculations similar to those discussed in the preceding subsection indicate that effectively this telescope should be able to see $10^{-5}$ supernovae pulses/sec-sr. In a balloon flight of $10^5$ sec-sr exposure it would have a 60-percent chance of seeing one or more such pulses.

Since galaxies do cluster, in actuality one can slightly improve the chances of positive results by pointing to a particular direction such as the Virgo ($\alpha = 12^h\ 28^m$, $\delta = +11°$) or Coma ($\alpha = 12^h\ 57^m$, $\delta = +28°$) cluster of galaxies where each contains over $10^3$ galaxies (Zwicky, 1965; Abell, 1965).

To gain additional information regarding the time dependence of the supernova pulse, monitoring the counting rates in the scintillations during a time interval of a few hundred microseconds subsequent to triggering is an attractive feature that can easily be incorporated in both of the suggested gamma-ray telescopes.

## Detection of Supernova Pulse by the Atmospheric Scintillation Method

Another powerful experimental approach to the problem of recording a supernova pulse of prompt photons is the detection of the fluorescence produced in the atmosphere by this electromagnetic radiation (Colgate, 1967a). Extensive work has been done by the Cornell cosmic-ray group in studying the fluorescence produced in the air by relativistic particles in air showers (Greisen, 1965; Bunner, 1966; Jenkins, 1966). It was shown by the above group and other workers in the field (Herzberg, 1950; Hartman, 1963; Davidson, 1964) that the fluorescence spectrum produced in the atmosphere consists basically of the $N_2$ second positive and the $N_2^+$ first negative band system of nitrogen and that an optical system designed to observe the spectrum between 3400Å to 4500Å would cover the useful range.

The fluorescence efficiency $\epsilon_{f1}$ of air of these wavelengths depends on the pressure P according to a function of the form

$$\epsilon_{f1} = \frac{K}{1 + \frac{P}{P_0}}$$

where K is a function of a particular line in a band and $P_0$ is a constant that depends on the particular band. Bunner (1966) gives the fluorescence efficiency of air at standard temperatures between 3400Å and 4500Å as

$$\epsilon_{f1} = \left(\frac{4.4}{1 + P/1.0} + \frac{0.92}{1 + P/15} + \frac{0.76}{1 + P/6.5} + \frac{0.27}{1 + P/4.6} + \frac{0.17}{1 + P/2.5}\right) \times 10^{-3} \tag{5}$$

where P is in mm of mercury. The efficiency, to the first approximation, is proportional to the square root of the temperature. With this knowledge it is possible to estimate the fluorescence produced by a supernova burst of photons interacting in the atmosphere.

The atmosphere is a very wide-band detection system, in which fluorescence will be produced by high-energy photons from the highest energies expected, a few Bev, down to energies near the visible where the radiation itself can be seen on the ground. The primary photons deposit their energy at different characteristic depths of the atmosphere depending on their energy. As a result, there will be characteristic pressure, or atmospheric depth, at which the fluorescence will be produced for a given energy. The fluorescent efficiency is a function of pressure; therefore, the efficiency will be a function of primary photon energy. Figure 5 shows the absorption coefficient and the fluorescence efficiency in air as a function of the primary photon energy. The fluorescent efficiency is calculated from Equation 5 with a first-order temperature correction based on a standard atmosphere.

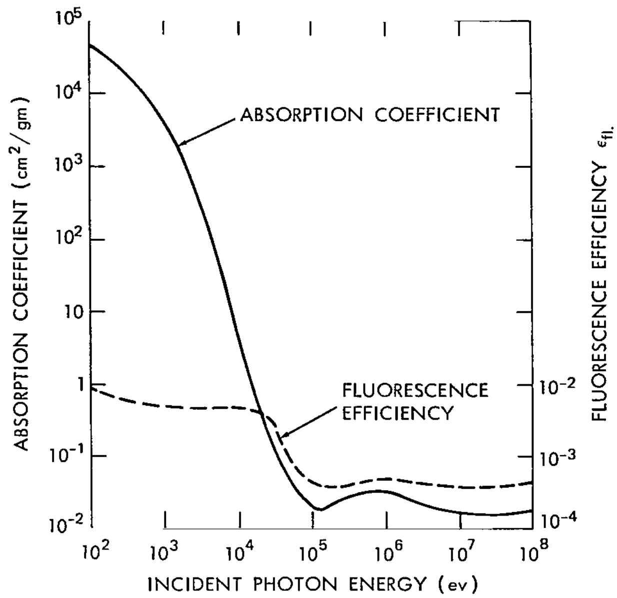



Figure 5—Absorption coefficient and fluorescence efficiency in the atmosphere as a function of the incident photon energy.

For photon energies above 100 kev, the Compton and pair-production cross sections are the dominant energy-loss mechanism; the deposition of the energy occurs at an altitude around 20 to 30 km where the fluorescence efficiency is around $5 \times 10^{-4}$. For photons below 10 kev the photoelectric process is the dominant energy loss mechanism. In this energy range the cross section increases rapidly with decreasing energy, causing the photons to deposit their energy at greatly varying depths in the atmosphere. However, at these higher altitudes the fluorescence efficiency is very close to its limiting value and does not vary appreciably from $5 \times 10^{-3}$. The fluorescence spectrum also changes as the characteristic pressure changes where the (IN) band dominates at high altitudes (low-energy photons) and 2P band at low altitudes (high-energy photons).

The fluorescence produced in the atmosphere by a pulse of photons could be seen by a photomultiplier tube on the ground; if it is an intense enough pulse, it could be distinguished from other events by its particular characteristics. For discussion purposes, a pulse of duration $\tau_{SN}$ (assumed to be tens of microseconds) and total energy $W_{SN}$ occurring at a distance R away will be considered. If this is followed by a lower-frequency radiation, there will simply be an addition to the pulse described below.

The high-energy photon pulse will deposit most of its energy in a band at a height h above the earth, as shown in Figure 6. If these photons have energies around 100 Mev, height h will be about 30 km. Since the supernova pulse will be incident upon the entire atmosphere, h is small compared

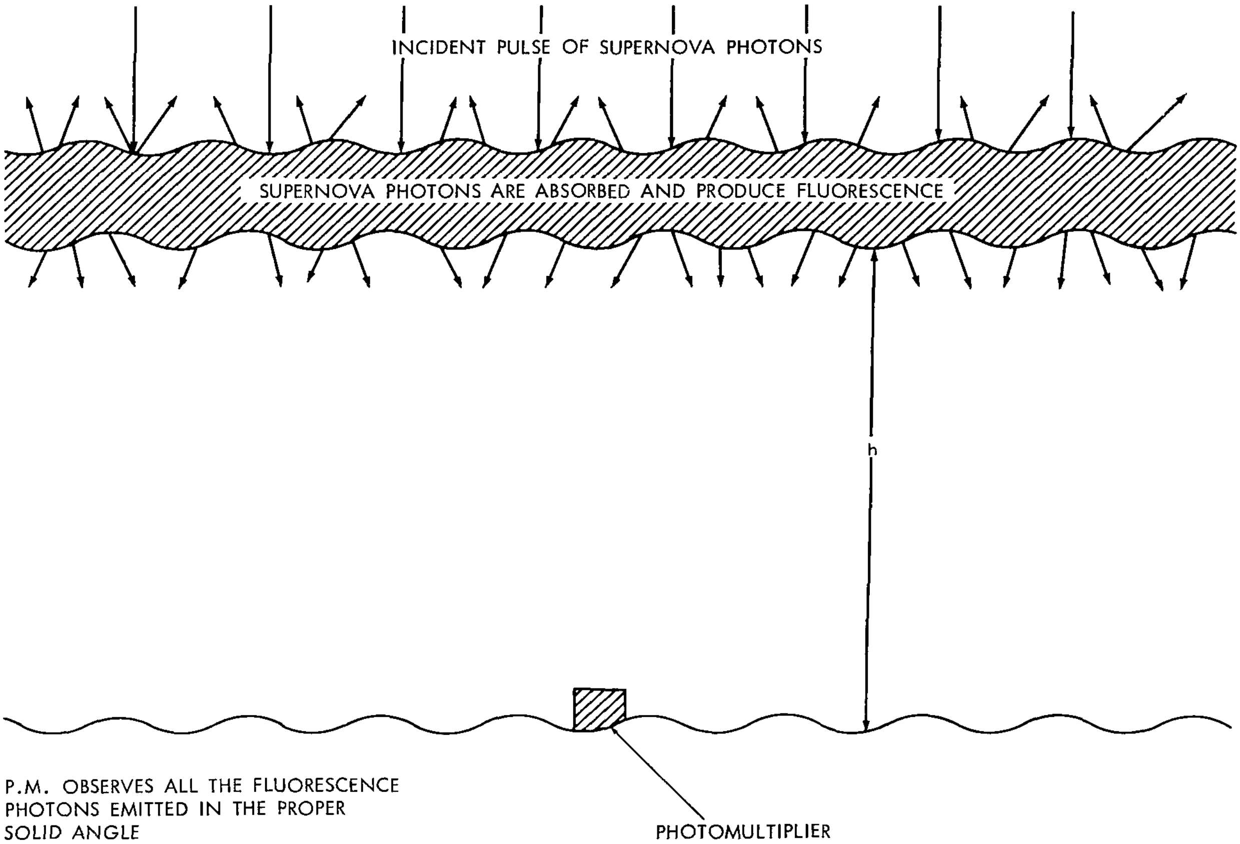



Figure 6—Schematic geometry of the supernova pulse in the atmosphere.

to the dimensions of the scintillating area which for the present purposes can be treated as a plane. To a first approximation—if we ignore attenuation effects and assume that the line to the supernova is not too far from the vertical—the optical flux reaching the photomultiplier is nearly isotropic in the upper hemisphere and contains half of the energy per unit area emitted in the fluorescent band—which is the energy per unit area of the incoming wave pulse times the fluorescent efficiency. Including a factor of 1/2 (which accounts approximately for the attenuation) the photon energy reaching the photomultiplier in the form of detectable photons is:

$$\frac{1}{4} \frac{W}{4\pi R^2} \epsilon_{f1} \quad . \tag{6}$$

Provided that $\tau_{SN}$, the length of the supernova pulse, is less than $h/c$, the characteristic height divided by the speed of light, the rise time of the output pulse from the photomultiplier is of the order of $\tau_{SN}$ and the decay time constant is approximately $h/c$, because light from further distances in the fluorescent layer arrives later. For the case of several hundred Mev photons, the values expected are $\tau_{SN} \sim 15$ microseconds, $h/c \sim 100$ microseconds.

If the initial high-energy supernova pulse is followed by lower-energy photons, whose characteristic pulse duration is longer but whose energy per decade of frequency is comparable, the photomultiplier output will be differently shaped; the main difference is that after the initial rise the pulse shape could be dominated by the supernova pulse characteristics rather than other considerations. The progressively later parts of the pulse will be increasingly affected by the lower-energy photons.

Our next requirement is to detect a pulse of the type just described against the night sky. The detecting system should be designed to look for signals which are significantly greater than background noise during integration time $\tau_i$ (typically $10^{-4}$ seconds).

Assuming $\tau_i \geq \tau_{SN}$, the total number of photoelectrons produced in the photomultiplier tube, S, is given by the expression

$$S \simeq \frac{A_{PM} W_{SN} \epsilon_{f1} \epsilon_{PM}}{16\pi R^2 E_v} , \tag{7}$$

where $A_{PM}$ is the area of the photomultiplier tube, $\epsilon_{PM}$ is the photomultiplier-photoelectron efficiency (typically $10^{-1}$), and $E_v$ is the average optical photon energy of $5 \times 10^{-12}$ ergs.

The total noise, N, due to the night-sky-background photon flux. B, during an integration time of $\tau_i$ is:

$$N \simeq BA_{PM} \tau_i \epsilon_{PM} , \tag{8}$$

which makes the signal-to-noise ratio

$$\frac{S}{\sqrt{N}} \simeq \frac{A_{PM}^{1/2} W_{SN} \epsilon_{f1} \epsilon_{PM}^{1/2}}{16\pi R^2 E_v B^{1/2} \tau_i^{1/2}} \tag{9}$$

By defining the unmistakable signal-to-noise ratio to be 10, the rate at which detectable supernovae pulses should occur can be calculated from the following equations:

$A_{PM} = 2.5 \times 10^2$ cm$^2$ (medium sized photomultiplier)

$W_{SN} = 5 \times 10^{47}$ ergs

$\epsilon_{f1} = 5 \times 10^{-4}$

$\epsilon_{PM} = 10^{-1}$

$E_v = 5 \times 10^{-12}$ ergs

$B = 10^7$ photon/cm$^2$-sec

$\tau_i = 10^{-4}$ seconds

$\rho_g = 5 \times 10^{-75}$ galaxies/cc

$f = 1$ supernova/50 yrs-galaxy (frequency)

The result indicates that the effective radius of observation is about $1.5 \times 10^{26}$ cm; this value of R then leads to an estimated number of three supernovae pulses per day using the frequency and source strength discussed earlier. Although the moon and weather conditions will limit the duty cycle of such an apparatus, assuming eight hours of useful observing time in a night with optimum conditions gives about one pulse a night. If the pulse integration time were increased to detect the fluorescence of the longer pulse of the lower-energy photons below 10 kev, the fluorescence efficiency would be increased by a factor of 10. However, the integration time would have to be increased by a factor of about $10^3$. Since the detection rate is proportional to $\epsilon_{f1}^{3/2} \tau_i^{-3/4}$, the supernova detecting rate would be reduced by a factor of 5.

It is interesting to note here that a post-explosion supernova model proposed by Morrison and Sartori (1966) and Morrison (1967) to explain the subsequent light curve postulates that $10^{51}$ ergs must be released during the explosion as ultraviolet photons in a matter of seconds. This large energy release in the optical band would extend detector sensitivity to sources as far away as $2 \times 10^{27}$ cm and therefore increases detection rate to about one hundred such pulses a night.

A possible detector system for observing the supernova pulse of prompt photons could be a direct adaption of an early system devised by Greisen and co-workers at Cornell University to detect air showers of around $10^{20}$ ev energy by the fluorescence produced in the atmosphere (Greisen, 1965, Bunner, 1966; Jenkins, 1966). Basically the system could contain several photomultiplier tubes with proper filters in front of them aimed at different directions, thus comprising a $2\pi$ detector. The outputs of tubes can then be displayed on cathode-ray tubes when two or more of the photomultiplier tubes have an integrated signal above the noise. Subsequently a camera can record on film the shapes displayed by the cathode-ray tubes as well as the time of the event. It is also possible to have several traces on the cathode ray tubes covering time scales of different magnitude. From the relative timing of the pulses in different tubes the direction of supernova could be estimated to an accuracy around 10 degrees.

Besides overcoming the night-sky background, as discussed in the preceding paragraphs, we must cope with other real-light pulses that exist in the atmosphere. Such signals could be due either to natural causes (lightning, auroral effects, Cerenkov light from air showers) or to man-made signals (airplanes, search light beacons, cars, etc.). However, with a multi-photomultiplier system such as the one discussed above, it should be possible to separate such signals on the basis of time scales and angular distribution of light. Observation of the signal in two different wavelength intervals can also help eliminate local effects as well as giving a rough spectral measurement of the supernova pulse.

The technique of definitely discriminating a supernova type pulse from local phenomena is to have two or more observation stations separated by a few hundred miles. While the local effects would be completely attenuated, the supernova pulse should appear basically the same in both stations. Subsequent comparison of the records of such stations could detect the coincidences. Furthermore, a correlation study with the optically observed supernovae should test the reliability of the results.

In case of promising results from expeditionary experiments, it is foreseeable that a network of ten or so such stations placed around the world could constitute an early supernova monitoring and warning system that could alert other experiments to study the subsequent phases of the explosion.

## CONCLUSION

Detection of a fast pulse from a supernova explosion is extremely important in determining whether supernovae explosions can accelerate particles to cosmic-ray energies. Regardless of the details of the explosion, the production of high-energy particles in dense regions requires fast-moving disturbances; this implies the generation of short-duration electromagnetic radiation. The merits and disadvantages of the two experimental systems to observe such a pulse seem to make them complementary experiments. The spark-chamber gamma-ray experiment will have good angular and energy resolution, but will have narrow bandwidth and smaller sensitivity. The atmospheric fluorescence detector, on the other hand, will be simpler to maintain, have a wide bandwidth and higher sensitivity but poor angular and spectral resolution of the incoming flux. Correlating data from these detectors with each other as well as with the optical supernova observations should yield a decisive evaluation of the results.

It is apparent that both experiments can either challenge or support the present-day theories of the supernova origin of cosmic rays and are therefore worth pursuing.

## NOTE ADDED IN PROOF

In recent conversations with Sterling Colgate, the authors confirmed that the pulse-width of the high energy photon pulse should be tens of nanoseconds in width rather than tens of microseconds. This small pulse-width enhances the probability of detecting such a gamma ray burst with a spark-chamber gamma-ray detector by a factor of about five, because the pulse-width is now much less than the sensitive time of the detector. This difference in pulse-width has no effect on the detection of a supernova pulse by the atmospheric scintillation method.

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