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**DISCOVERY OF INTENSE GAMMA-RAY FLASHES
OF ATMOSPHERIC ORIGIN**

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Abstract

Observations have been made of a new terrestrial phenomenon: brief (~ millisecond), intense flashes of gamma rays, observed with space-borne detectors. These flashes must originate at altitudes in the atmosphere above at least 30 km in order to be observable by orbiting detectors aboard the Compton Gamma-Ray Observatory (CGRO). At least a dozen events have been detected over the past 2 years. The photon spectra from the events are very hard and are consistent with bremsstrahlung emission from energetic (MeV) electrons. The most likely origin of these high energy electrons, while speculative at this time, is a rare type of high altitude electrical discharge above thunderstorm regions.

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We report here the serendipitous detection of high-energy photons from the Earth's upper atmosphere, observed by the Burst and Transient Source Experiment¹ (BATSE) on the CGRO. Their apparent correlation with storm systems leads us to implicate as their cause, electrical discharges from these systems to the stratosphere/ionosphere. Runaway discharges to the ionosphere had been predicted in the early literature^{2,3} and modeled in detail previously.⁴ These gamma-ray events may also be related to recently recorded optical discharge phenomena above thunderstorms⁵ and to other cloud-to-stratosphere discharges that have been reported in the past.^{6,7}

The Compton Observatory was launched in April 1991 to perform observations of celestial gamma-ray sources. The BATSE experiment¹ is one of four experiments on the observatory. It serves as an all-sky monitor and has detected over 800 cosmic gamma-ray bursts, several hard x-ray transients, numerous persistent and pulsed hard x-ray sources and several thousand solar flares. In addition to these celestial sources, on rare occasions BATSE has responded to gamma-ray flashes from the Earth, previously unreported.

BATSE consists of an array of eight detector modules located at the corners of the observatory, arranged to provide maximum unobstructed sky coverage. The scintillation detectors are sensitive to photons with energies above 20 keV. The geometry of the array results in sources usually being observed by four detectors. Data from the detectors are processed onboard by a data system which sorts the data into several data types with different temporal and spectral resolutions.¹ The gamma-ray flashes reported here triggered an onboard burst data recording mode, allowing high time resolution observations of the events in most instances. Sources are located by comparing the relative responses of the detectors which view different directions.^{8,9}

give average duration here?

The unique features of the terrestrial events reported here are their extremely hard spectra and their short duration. They are very different from other events which have triggered the detectors such as gamma-ray bursts, solar flares, fluctuations of other known hard x-ray and gamma-ray sources,

and bremsstrahlung from precipitating magnetospheric electrons. Furthermore, these events are located by the BATSE detectors as emanating from below the local horizon. The events that trigger the BATSE detectors are relatively rare, occurring less than once every 2 months. It is likely that other, weaker events of similar origin go undetected due to the trigger criteria implemented by the experiment.^{1,8} Since the minimum sampling time for triggering the BATSE burst mode is 64 ms, these events must be at least ^{much shorter} ~40 standard deviations above the background rate in at least two detectors in order to trigger the onboard system.

It is believed that prior instrumentation and experiments were incapable of detecting this phenomenon for several reasons, or these events were overlooked as being spurious. Most detectors used in high-energy astronomy are collimated and would likely have missed these rare events and/or data are not analyzed during Earth-viewing times. Also, the temporal resolution of most experiments would not have been able to respond to these very brief events and would thus have had poor signal-to-noise when sampled with coarser time resolution. The BATSE array of multiple, independent detectors viewing different directions gives us confidence in the reality of these events as opposed to some instrumental or spacecraft effect such as electronic noise. The multiple, wide-field detectors also allow a direction determination to be made for each event.⁸ The observed counting rate ratios of the detectors are consistent with the source of these events originating from a large distance relative to the spacecraft dimensions. BATSE also contains plastic scintillation detectors which are sensitive to charged particles above ~500 keV. There were no detectable increases in the rates from the charged particle detectors accompanying these events. Finally, independent detectors on another experiment (the Oriented Scintillation Spectrometer Experiment (OSSE)) on the observatory confirm these gamma-ray observations (G. Share, private communication).

note: (The assumption in Lueburst is that the gamma-rays originate from a point source at infinity)

Although the typical location accuracy for strong cosmic gamma-ray bursts is ~ 3 degrees, ~~it is estimated that~~ ^{these cannot be quoted to} the location accuracy of ~~the~~ ^{or} events described here is perhaps not better than 10 to 20 degrees. This is due to several causes—among them being the limited counting statistics in the detectors, ^{and} the hard spectra which lead to increased scattering and transmission through the backside of the detectors, ~~and the software used to derive locations, which assumes that sources are above the horizon.~~ Also, the angular extent of the emission is not well-determined from these observations alone. The resulting angular uncertainty implies a positional uncertainty from a few hundred kilometers to perhaps a thousand kilometers, depending primarily on the observed geocenter angle (the angle from the nadir).

which result in the location software operating in a regime where it has not been extensively calibrated.

Table 1 lists the data relevant to 12 events recorded between April 1991 and October 1993. We have obtained concurrent weather images for five of the events, as indicated in the Table. In each of these photos, large weather systems, presumed to have severe thunderstorm activity, are seen in the direction of the located events. The probability of this occurrence is very small, since it is estimated that $< 5\%$ of the Earth's surface area at these latitudes is covered by thunderstorms at any instant. Figure 1 shows the spacecraft location at the time of all twelve of the events along with a contour map of thunderstorm activity over the world.¹⁰ The correlation of these two phenomena is quite evident.

The BATSE data type with high time resolution used to study the gamma-ray flashes reported here is time-tagged event (TTE) data. These data are usually recorded whenever the onboard trigger system is enabled. However, sometimes these data are overwritten or otherwise unavailable due to telemetry gaps. In these cases, only data with 64 ms time resolution are available. The TTE data consists of up to 32 k individual scintillation detector events that are identified by the detector module that recorded it, the energy channel (one of four channels), and the arrival time recorded with a resolution of $2 \mu\text{s}$ (relative timing accuracy). The four energy channels cover the following approximate energy ranges: 20 to 50 keV, 50 to 100 keV, 100 to 300 keV, and > 300 keV. A

we could get an order of magnitude estimate of this probability by RMSing the % of surface area enclosed by the 10 location contour with the 5% and taking the product of these 5 values

continuously operating digital ring buffer allows the recording of approximately 8 k events prior to the time of the trigger recognition. These pre-trigger data have been essential in our studies of short timescale phenomena such as these events. The time profiles of these events are shown in Figure 2. They consist almost entirely of pre-trigger data. Five of the events consist of two closely-spaced pulses, from 1 to 4 ms, and one event has at least five distinct pulses of similar shape but variable spacing. The estimated typical gamma-ray energy fluence of these events is of the order $\sim 10^8$ to 10^9 ergs, assuming isotropic emission and a typical distance to the source of 500 km.

in our energy range? above 20keV?

The spectral information that is available from these events is limited, since only four coarse energy channels (as given above) are recorded in these short time intervals. Hardness ratios (HR) of different combinations of two of the energy channels have been useful in studying the gross spectral characteristics of cosmic gamma-ray bursts and soft gamma repeaters.^{11,12} It is found that the HR 3/2 for these terrestrial events are about 2.0 times that measured for the average gamma-ray burst and 1.4 times the value of a subset of gamma-ray bursts with particularly hard spectra. The values for HR 4/1 show an even greater separation between the two types of phenomena. However, the HR 4/1 parameter has a high statistical uncertainty in many cases due to the limited counts observed in one or both of those two channels. The measured hardness ratios of these events are also considerably higher than those measured by BATSE from any other cosmic sources such as the Crab Nebula or from bremsstrahlung from precipitating electrons from the Earth's magnetosphere. A model-dependent spectral deconvolution of BATSE four-channel data has also been developed.¹³ It is found that a hard bremsstrahlung spectrum with a characteristic energy of 1 MeV is consistent with the observed hardness ratios of all of these events.

In addition to the events listed in Table 1, during the same time interval covered by these events (30 months), there have been at least five other triggered events which are suspected to be of this same type. However, high time resolution data were not available for these events, so that the nature of these is problematic. Also, there are three other triggered events which had considerably

I think 2 of the spectra favoured hardening at the lower energies

longer duration and/or it could not be well-determined that they originated from the Earth-facing direction. Since it is not certain that they are in this same category of events, they have not been included in Table 1. Thus, the total event count in this time interval is between ~12 and 20. The instantaneous area on the Earth observable by the spacecraft is $\sim 1 \times 10^7$ km.² This indicates the rarity of these events.

The possibility of strong electric fields producing ionization at altitudes high above the tops of thunderstorms was first discussed about 70 years ago;^{2,3} as it was recognized that sudden, strong changes in the thunderstorm electric field due to a lightning discharge might be capable of producing ionization in the upper atmosphere. If the fields were intense enough, over a large area, they would be capable of not only ionizing the atmosphere but of producing “runaway” electrons and subsequent bremsstrahlung x-rays. The key to the occurrence of this phenomenon is the fact that the electric field due to lightning falls off less rapidly with height above the cloud than does the atmospheric density, which determines the breakdown potential of the air. This might occur, for instance, if the electric field strength at 60 km altitude were to exceed approximately 500 v/m. Simple electrostatic calculations predict field changes on this order whenever the lightning charge transferred in the cloud is on the order of 300 coulombs. This is a very large charge but has been observed in intense storm systems.¹⁴

A field of 500 v/m would have to accelerate electrons over a distance of several kilometers in order to achieve the MeV electrons necessary to produce the observed gamma-ray events. The glow-like discharges that have recently been observed^{5,6} appear to occur over heights between 40 and 80 km. They extend well over 10 km in height and from 10 to 50 km in horizontal extent. These events seem to occur over large, horizontally extended storm systems which may be capable of producing the large electric field changes required to directly ionize the atmosphere and, perhaps, produce high-energy electrons.

At least 18 upward-going lightning events have been detected from the space shuttle.^{15,16} A number of these events seemed to be quite intense. Some appeared to be connected to the parent cloud; others show no visible connection. All of the events appeared to have horizontal and vertical extents in excess of 10 km. In addition to these well-documented observations, there have been numerous reports by aircraft pilots of upward discharges to the atmosphere but these have not been treated in the scientific literature.⁷ It should be noted that x-rays produced in thunderstorms have been measured on various occasions,¹⁷ although these measurements were made inside the storms at low (tropospheric) altitudes. These x-rays have also been explained by bremsstrahlung from accelerated MeV electrons.¹⁸

Numerous observations of lightning discharges have been made from high-flying aircraft.¹⁹ The timescales of these optical signatures and electric field disturbances seen are of the same order as that of the events observed in the present work (~0.5-1 ms). Thus, an impulsive, high-energy discharge of limited extent seems to be implicated. Any widespread discharge (over 100 km) would not be compatible with the observations, considering the photon travel time and the extensive gamma-ray scattering which occurs within the atmosphere. Observations of short cosmic gamma-ray bursts by BATSE have shown substantial (ms) time delay due to atmospheric scattering.²⁰

No prior references to gamma radiation from atmospheric electrical discharges (or from electrons in the magnetosphere) have been found in the literature. Because of the new and unique nature of these events, the lack of correlated observations in other spectral regions, and the paucity of concurrent weather data, the exact cause of the phenomenon must await further study. Although a detailed cause of these events is lacking, we are convinced of the reality of the observations because of our experience with the instrumentation accumulated over the past 2 years of operation in orbit, along with the extensive observations of a wide variety of celestial sources with the same experiment.

Acknowledgments:

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Table 1. A list of the 12 events described in this paper and shown in Figures 1 and 2. The geocenter angle is measured from the nadir. (The Earth's horizon, as viewed from the spacecraft, is approximately 70 degrees from the nadir.) The location given is that of the spacecraft at the time of the event, not necessarily the location of the origin of the event.

BATSE Trigger Number	Date	Time (UTs)	Geocenter Angle (deg)	Spacecraft Location	
				Latitude (deg)	Long. (E) (deg)
106 *	22 April 1991	02533	35	6	75
868 *	05 Oct. 1991	12711	54	8	359
1433 *	24 Feb. 1992	36549	39	-16	39
1457 *	01 March 1992	81252	46	-7	296
2144	24 Jan. 1993	54533	45	6	79
2185 *	11 Feb. 1993	53095	73	-5	119
2223	06 March 1993	52583	44	3	115
2348 *	20 May 1993	07337	59	11	254
2370	03 June 1993	14440	25	18	125
2457	23 July 1993	18386	15	28	110
2465	26 July 1993	16888	39	26	112
2573	09 Oct. 1993	38648	31	-24	238

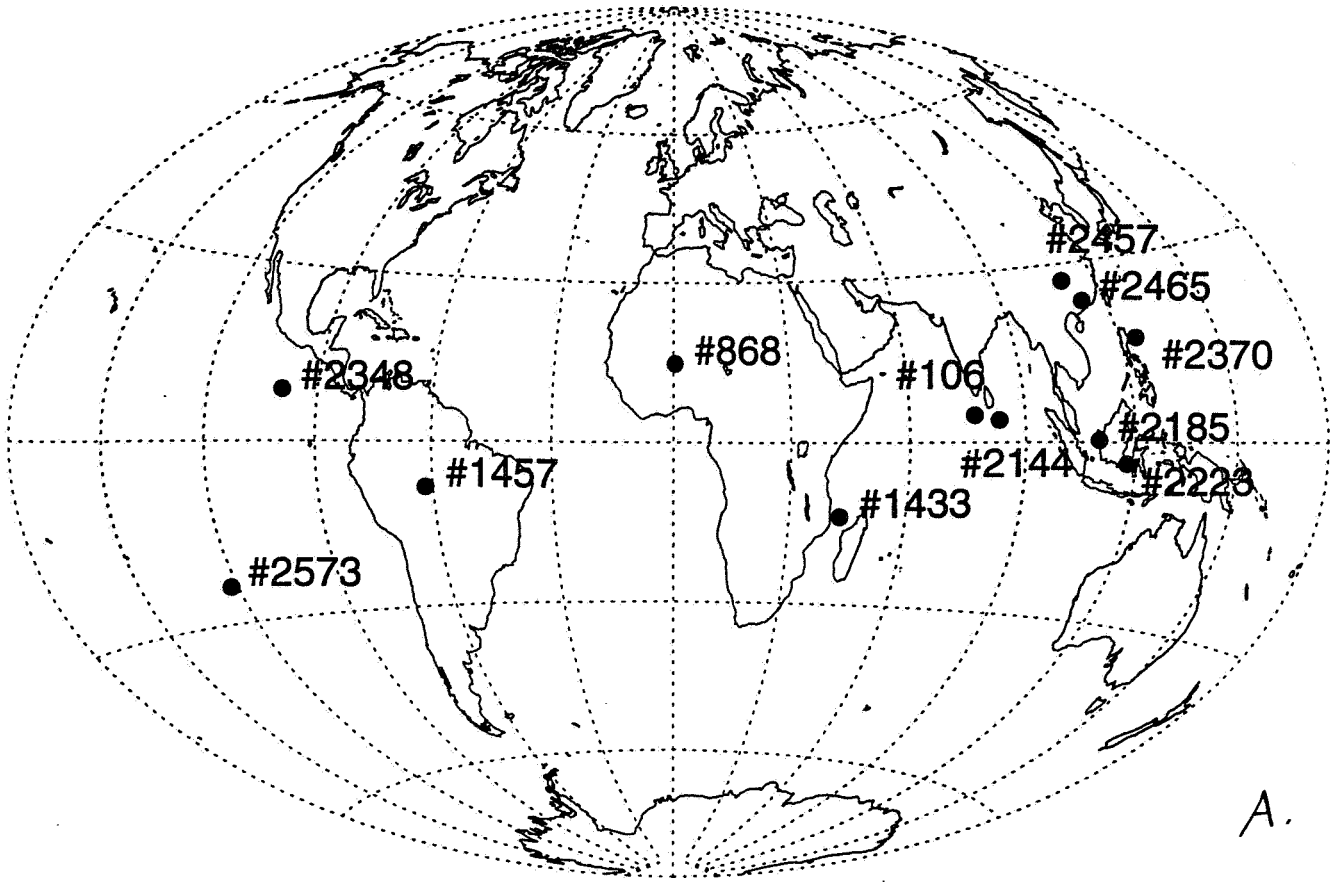
*Weather photo available

Figure Captions:

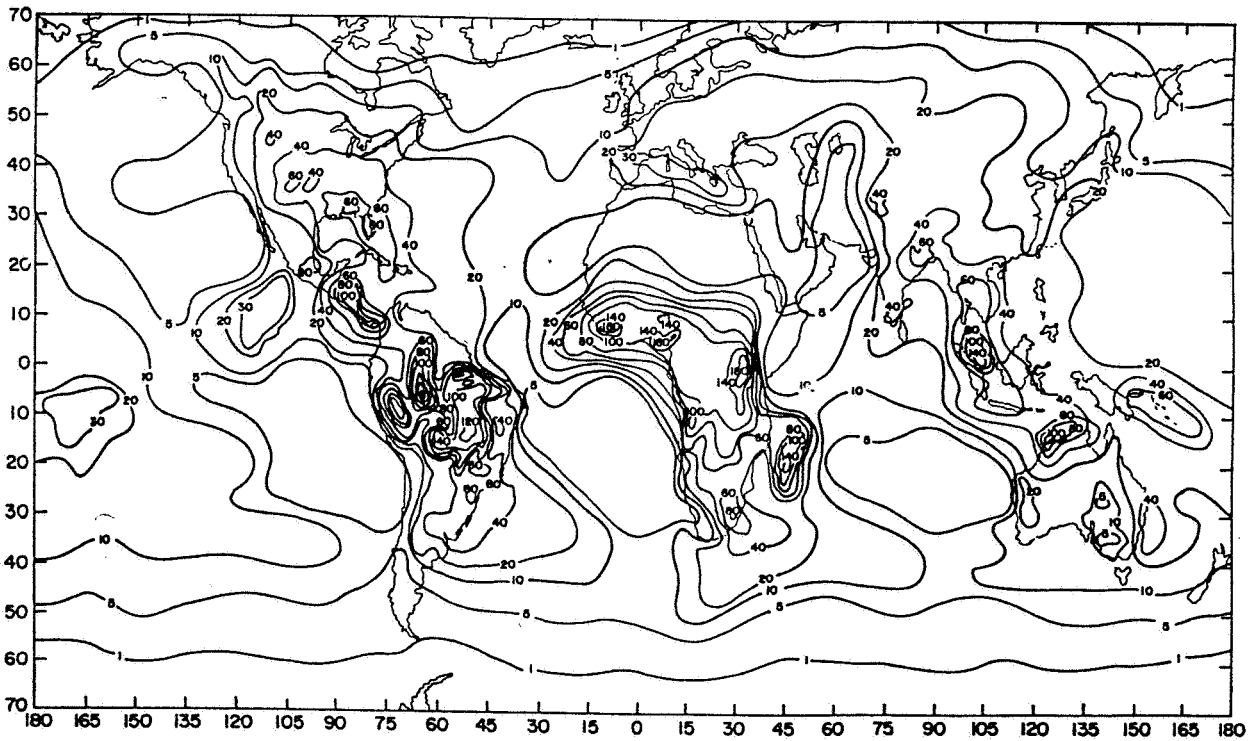
Figure 1. A) The approximate locations of the events of Table 1 over the Earth.

B) Contour map of the yearly thunderstorm activity over the Earth (from WMO). No events occurred over the ocean regions which are usually devoid of thunderstorms. The spacecraft is limited by its orbital inclination to latitudes below 28.5 degrees.

Figure 2. Time profiles of the events listed in Table 1 (arbitrary start time). The time resolution of the plots is 0.1 ms per bin. Multiple peaks are evident in many of the events, with peak separations from 1 to 4 ms. Typical rise and fall times are ~0.1 to 2 ms.



A.



B.

Fig. 1

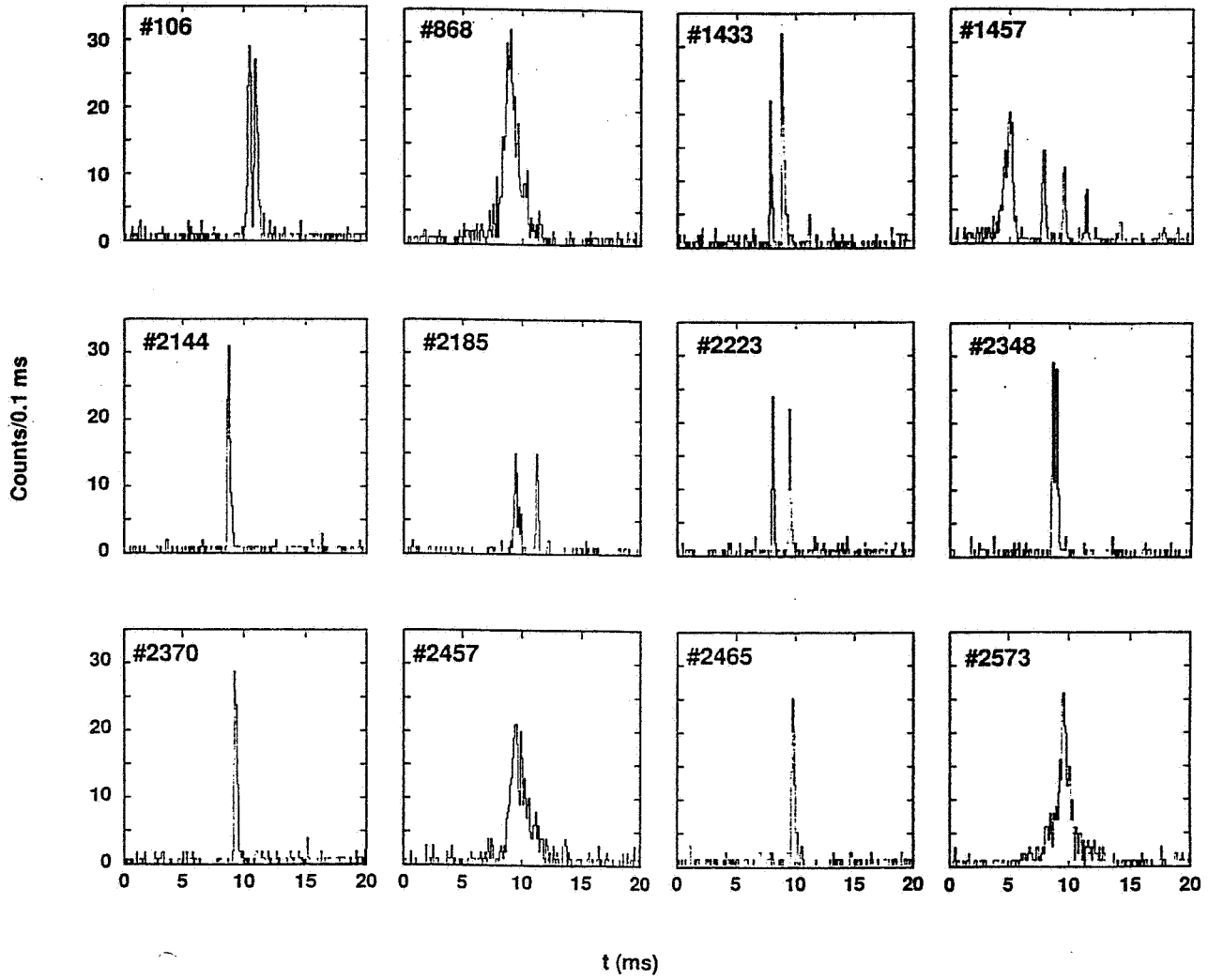


Fig. 2

P-3 → Fig. (#2348) GOES-7 infrared image (MB enhancement) on 20 May 1993 at 0201 UTC resampled to a spatial resolution of 8 km. The storm is located in the Inter Tropical Convergence Zone southeast of the GRO position. The cloud has a minimum cloud top blackbody temperature of 193 K which is equal to the minimum detectable level of the infrared sensor. During the period 0200 - 0206 UTC the U.S. based National Lightning Detection Network detected 11 cloud-to-ground lightning discharges associated with this storm.

Fig. (#868) METEOSAT 4 infrared image on 5 October 1991 at 0325 UTC. Isolated storm cells ahead of a broad area of trailing stratiform cloudiness can be seen over Nigeria east of the GRO position. METEOSAT image supplied by the European Space Agency.

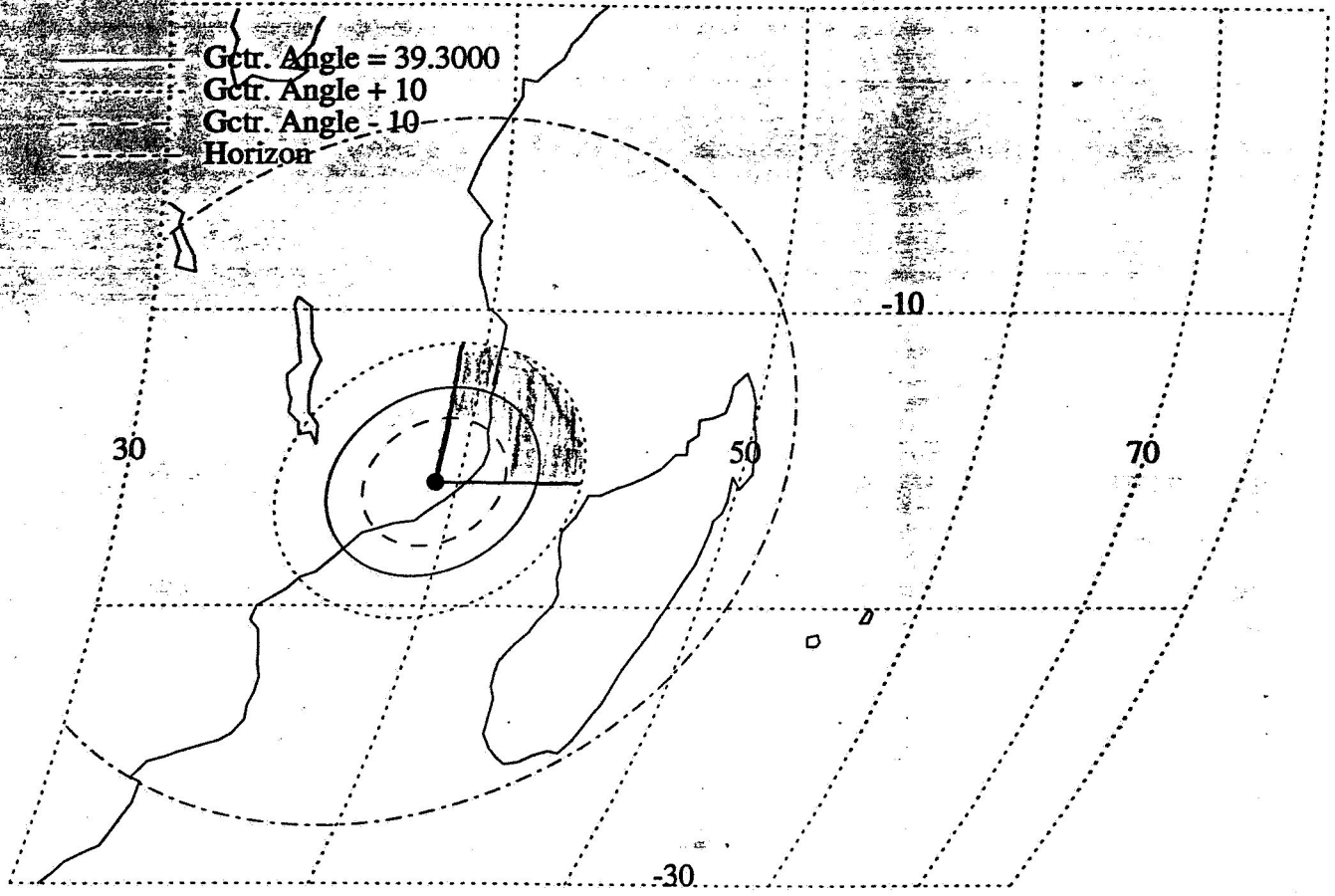
P-1 → Fig. (#1433) METEOSAT 4 infrared image on 24 February 1992 at 0955 UTC. A large cyclone between Madagascar and the African continent can be seen east of the GRO position. METEOSAT image supplied by the European Space Agency.

Fig. (#1457) METEOSAT 3 infrared image on 1 March 1992 at 0225 UTC. A number of isolated thunderstorm cells north of Equador can be seen to the south of the GRO position. METEOSAT image supplied by the European Space Agency.

P-2 → #106 INSAT

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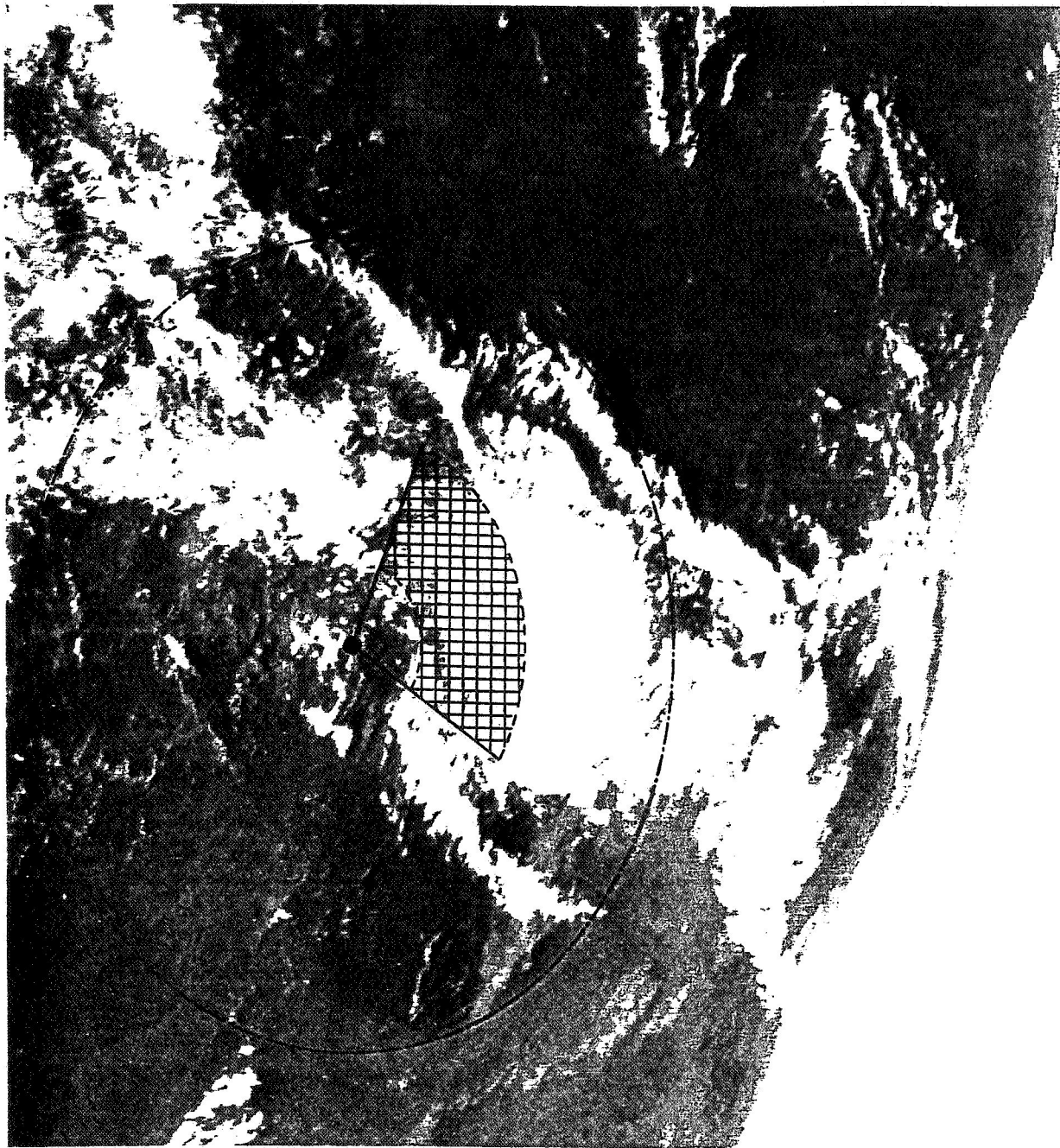
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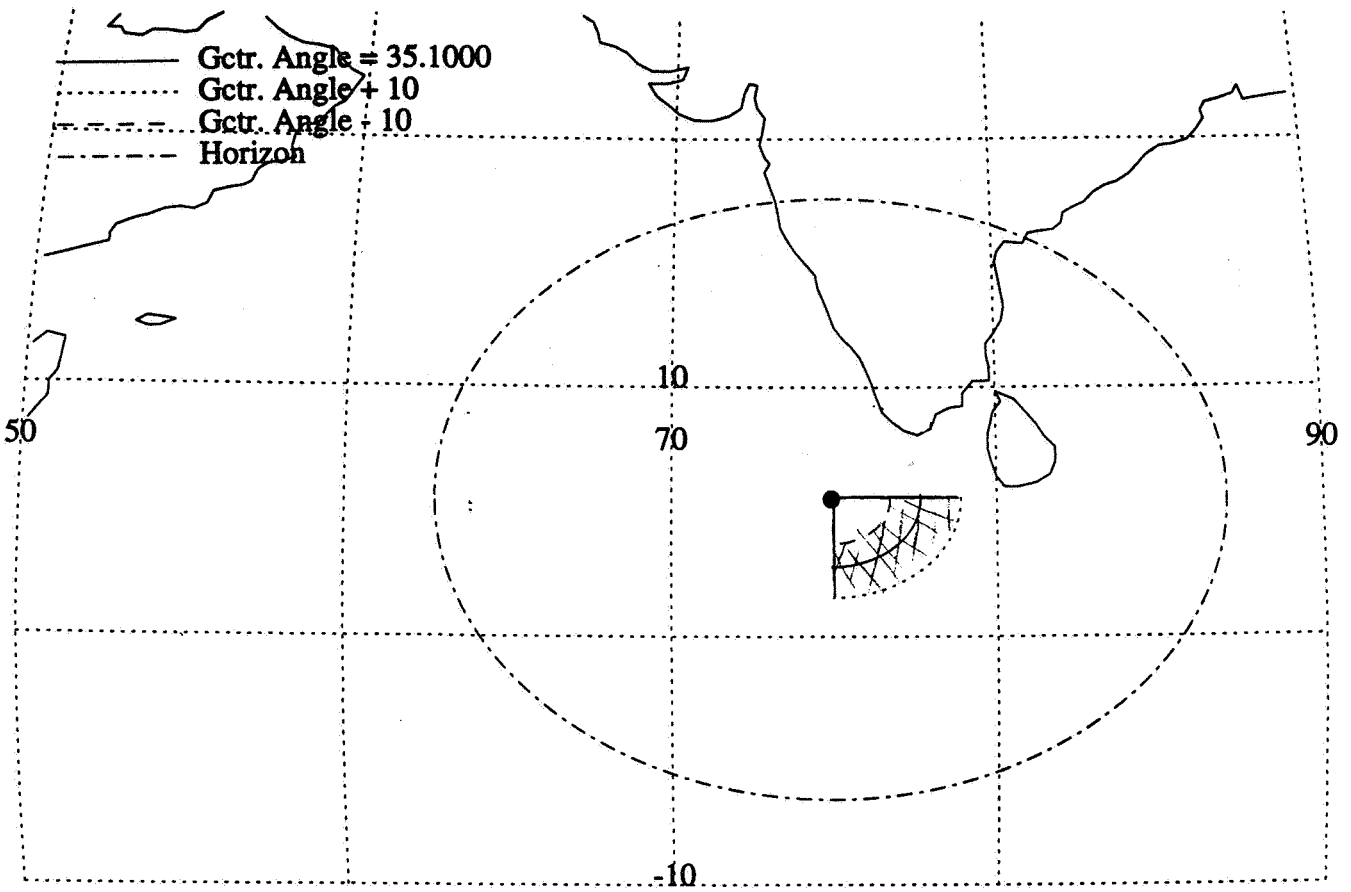
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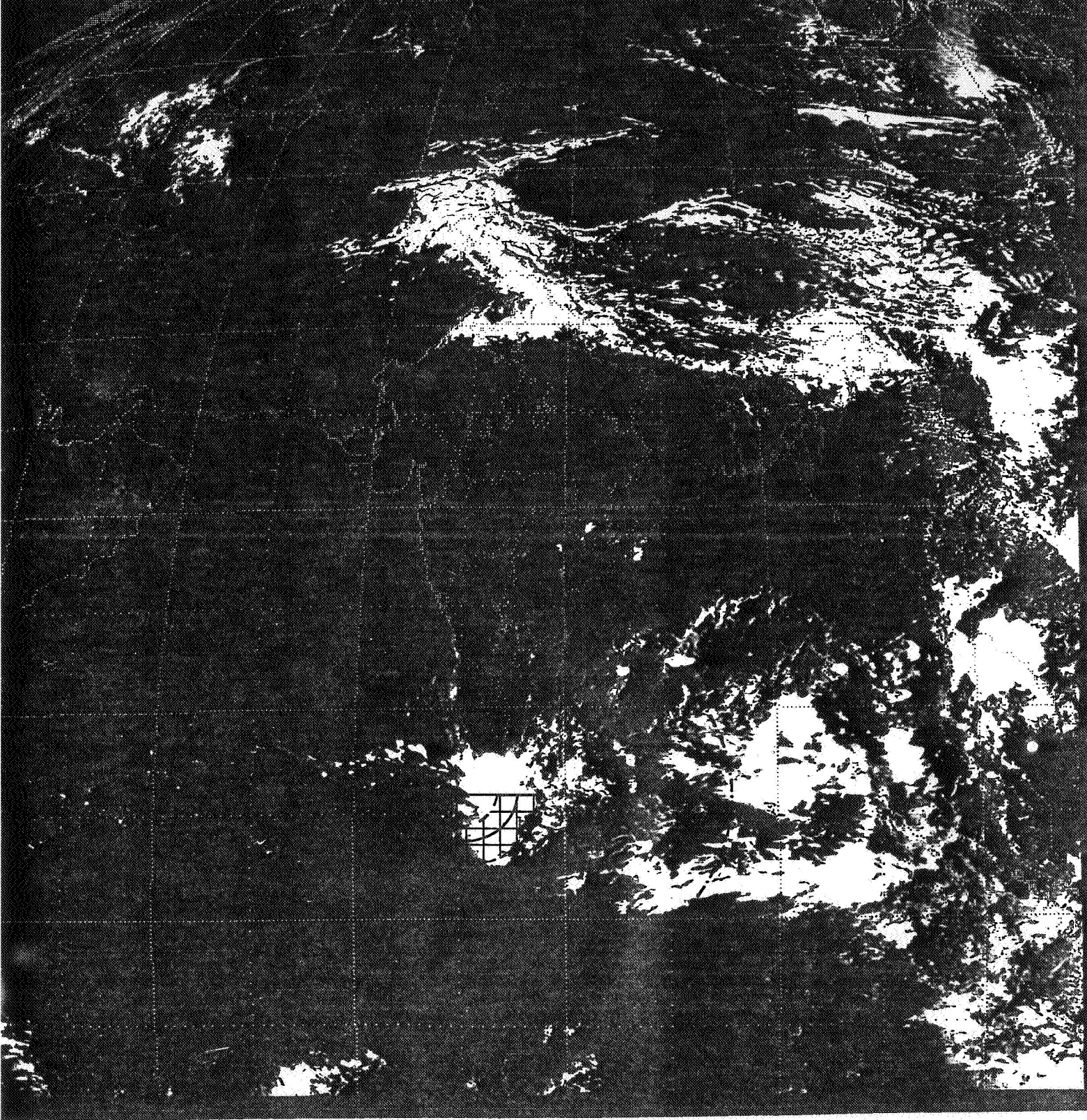
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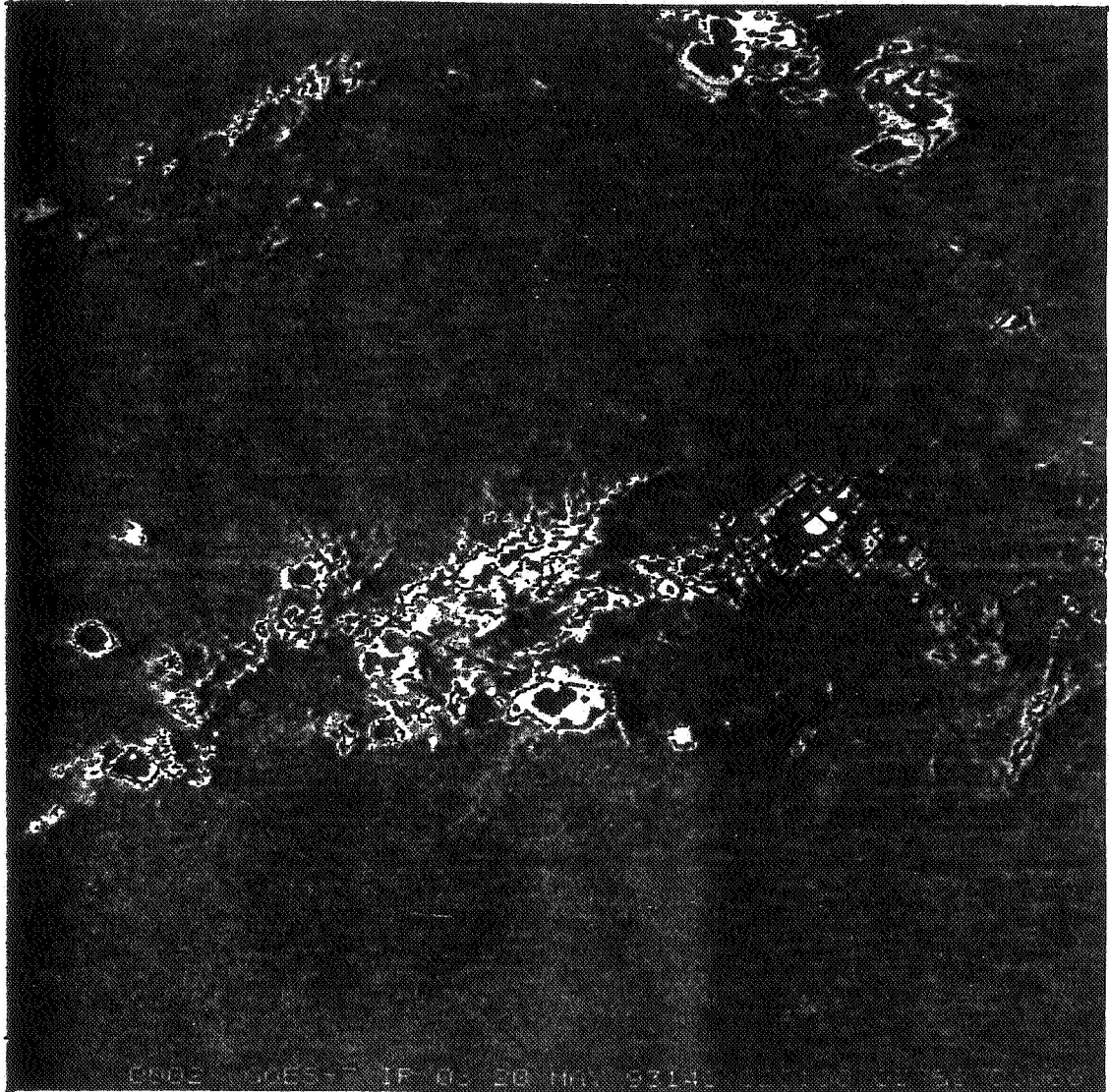
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P-3

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