(NASA-TM-84966) THE SOURCE OF SATURN ELECTROSTATIC DISCHARGES: ATMOSPHERIC STORMS (NASA) 19 p HC A02/MF A01 CSCL 03B

N83-18629

Unclas
G3/91 08500

NASA

Technical Memorandum 84966

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JANUARY 1983

National Aeronautics and
Space Administration

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THE SOURCE OF SATURN ELECTROSTATIC DISCHARGES: ATMOSPHE:'IC STORMS

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Submitted to Nature

Abstract

Important properties of the recently-discovered Saturn Electrostatic Discharges are entirely consistent with an extended lightning storm system in Saturn's atmosphere. The presently favored B-ring location is ruled out.

The Voyager spacecraft planetary radio astronomy (PRA) experiments detected an unusual impulsive (15-400 msec), broadband (20 kHz to 40 MHz) radio emission component that persisted throughout the two Saturn encounter periods[1,2]. These short bursts of emission tended to be grouped into episodes which recurred with a period of about 10h 10m, distinctly faster than the Saturnian rotation period of 10h 39.4m[1-5]. This periodicity considered together with the occurrence dependence on distance from Saturn led Warwick et al.[1] to conclude that the bursts were related to the Saturn system and coined the term SED for Saturn Electrostatic Discharges. Only two source locations were deemed possible[1] based on the repetition period: the atmosphere at equatorial latitudes where ground-based Doppler measurements[6] and Voyager imaging measurements[7,8] show cloud top wind velocities corresponding to a 10h 10m rotation period, and a discrete source in the rings at 1.8 R_s (R_s = Saturn radius = 60330 km) where the Keplerian revolution period equals 10h 10m. Atmospheric source locations initially were ruled out[1] because the ionospheric electron density measured by the radio science experiments on the Pioneer 11 and Voyager spacecraft[9-11] was sufficient to prevent escape of emission much below 1 MHz, whereas SED were sometimes detected to frequencies as low as 20 kHz. Several papers were then published[2-5] discussing the ring source alternative. However, Burns et al.[12] pointed out that the ring system casts a large shadow on the equatorial ionosphere, perhaps reducing the ionospheric electron density in this region enough to permit escape of the low frequency atmospheric (e.g. thunderstorm) radio noise. However the weight of evidence still appeared to favor the ring-source hypothesis and no evidence has been brought forth until now to resolve this controversy.

We have analysed the SED observations with particular attention given to the spacecraft-Saturn geometry during the Voyager-1 encounter. We conclude that SED are not generated by a localized or distributed source in Keplerian orbit about the planet but appear to be the manifestation of a long-lived atmospheric storm or system of storms in Saturn's equatorial zone extending some 60 degrees in Saturn longitude.

SED Episodes

Figure 1a is a schematic diagram of the occurrence of SED as a function of time and frequency during the period immediately surrounding the Voyager 1 encounter. This summary was constructed from visual inspection of high resolution dynamic spectrograms; thus it does not suffer from misidentification of spacecraft interference to which computer SED recognition algorithms are subject. (The comparable plot from Voyager-2 is not as well ordered due to the lower occurrence rate of SED and the somewhat poorer definition of SED episodes. This difference between Voyager-1 and Voyager-2 results is discussed later.) There are three features of crucial importance evident in Fig. 1a:

(1) the frequency extent of SED varies systematically with time. For the two

episodes before closest approach (and for all prior episodes not shown in Fig. 1a), the SED are not observed below approximately 4 MHz. During the closest approach interval and for all episodes after closest approach, SED are detected to frequencies at least as low as 100 kHz.

(2) outside of the shaded intervals in Fig. 1a, close scrutiny of the high resolution PRA data shows that there are indeed NO detectable SED.

(3) the appearances and disappearances of SED episodes are independent of frequency except for the onset of the episode centered on closest approach. For this one onset, SED are first detected at the highest PRA frequencies near 40 MHz and gradually over a 4 hour period fill the entire band. This last feature has been noted previously[3].

Problems with Previous Theories

The total lack of SED between episodes strongly suggests that the source region is being occulted once per revolution by the planet. The typical duration of the "occultations" in Fig. 1a is greater than 3 hours, or roughly one third of the period of SED even when the motion of the spacecraft past Saturn is taken into account. This duration corresponds to roughly 120 degrees of the SED "orbit". If indeed the pattern shown in Fig. 1a represents a source undergoing consecutive occultations, then an isotropically radiating point source at 1.8 R_s suggested by Warwick et al.[1,2] and Evans et al.[3-5] is not possible because such an object would be out of view for only about 2 hours or less. Figure 1d shows the occultation pattern that would result from a point source in the B-ring at 1.8 R_s aligned so that its reappearance times match the observations in Fig. 1a. The black bands correspond to times when the source should be in view from Voyager and the intervals in between are times when the source should be occulted by the planet. On the other hand, a point source in the equatorial atmosphere would be beyond Voyager's horizon for considerably more than 180 degrees of rotation (or more than 5 hours) unless SED are somehow able to transmit over the horizon. This eliminates the possibility of a single localised storm in the equatorial atmosphere producing SED. Figure 1c shows the occultation pattern to be expected from a single isolated storm in the equatorial region. Additionally, the 4 MHz low frequency cutoff observed before closest approach is extremely difficult to explain with a ring source due to the lack of intervening high density plasma, although for an atmospheric source, radio emission would necessarily pass through the planetary ionosphere suffering some refraction which could produce the observed cutoff.

Equatorial Lightning Storms

We can see no way in which the ring source theory can be modified so that all three of the previously mentioned observed parameters can be met. An extended source in the rings, for example, would be occulted even less than a point source. Some modification to the assumed isotropic radiation pattern might be invoked to explain the duration of the occultations, but this cannot explain the low frequency cutoff. We propose instead that the SED are generated by a storm system in Saturn's equatorial region atmosphere spread over an extended swath in longitude. We determine the longitude of the leading edge of the storm from any of the reappearance times shown in Fig. 1a, and similarly, we find the longitude of the trailing edge from any of the disappearance times.

Since this storm system moves at a rate different from the planetary rotation rate of 10h 39.4m, our determination of the storm's longitude in the Saturn longitude system[13] applies to a specific time. We have determined the storm's boundaries as 210 and 270 degrees SLS for the leading and trailing edges, respectively at the epoch 15:10 (spacecraft time) on day 317 of 1980. Using the Voyager trajectory information to determine the occultation times of this storm system as observed from Voyager, we obtain the schematic pattern shown in Fig. 1b. Here, the black bands represent times when all or part of the 60 degree-wide source region is within view of the spacecraft, and the intervals in between are times when the source region is completely occulted by Saturn. The remarkable degree of similarity between Fig. 1a and Fig. 1b contrasted with the lack of agreement between Fig. 1a and either Figs. 1c or 1d strongly suggests that the disappearance and reappearance of SED is caused by occultation and reemergence of an extended equatorial storm system.

In addition to locating the storm in longitude, some restrictions can be placed on its latitudinal extent. The uncertainty in the SED period of ± 5 min[2] corresponds to an equatorial cloud top wind speed range of ± 80 m/sec. Inspection of the Voyager-1 wind velocity profile deduced from the imaging data[7] indicates that the storm must be centered at the latitude of peak wind which is +4 degrees. The spread in latitude centered on +4 degrees which corresponds to ± 80 m/sec is only about ± 2 degrees. However, no wind velocity data is shown for the latitude band obscured from view by either the rings or the shadow of the rings, so the possibility exists that SED may emanate from that region.

As mentioned previously, the observed low-frequency cutoff is also consistent with propagation of radio waves through the Saturnian ionosphere. Prior to encounter, when only frequencies greater than about 4 MHz are observed, Voyager-1 was above the daylit hemisphere of Saturn, at a near-equatorial latitude and midway between the noon meridian and dusk. The radio emission generated by the storm system would necessarily propagate through the dayside Saturnian ionosphere in order to reach the spacecraft. Since radio waves cannot propagate at frequencies below the electron plasma frequency, we propose that the low frequency cutoff of the SED is caused by high electron densities in the dayside Saturnian ionosphere. The maximum electron density is estimated from $f_p = 9 N_e^{1/2}$ where f_p is the electron plasma frequency in kilohertz and N_e is the electron density in electrons per cm^3. Equating the 4 MHz cutoff to the plasma frequency, the implied maximum electron density in the ionosphere at the sub spacecraft point is 2×10^5 cm^{-3}. This is about an order of magnitude larger than the electron densities deduced from radio occultation measurements[9-11]. However, those measurements were made near the dawn and dusk terminators, whereas the density derived here applies to mid afternoon. This change in density from terminator to mid afternoon is comparable with the diurnal variation of electron density observed at the earth[14]. Only during and after the closest approach are the very low frequency (< 100 kHz) SED observed. It is also during this period that Voyager observes the storms through the nightside ionosphere. This implies a maximum electron density in some portions of the nightside ionosphere of 100 cm^{-3} or less, again not inconsistent with day-night variations for some parts of the earth's ionosphere[14].

The frequency dependent onset of SED observed just prior to closest approach can also be understood in terms of an atmospheric source. Figure 2 shows an equator plane projection of the Voyager-1 trajectory during the near encounter period. Inset in Fig.2 are three views of Saturn and the storm system as seen from Voyager-1 at the indicated times. Panel (a) corresponds to the view about 1 hour after the reappearance of SED when the leading edge of the storm system (fixed at the location described above) has just become visible. The radio emission accompanying this storm system transmits through a long path in the ionosphere when it first appears on the observer's horizon resulting in considerable refraction. We have performed ray tracing analyses which demonstrate that high frequencies (>30 MHz) are able to propagate directly to the spacecraft even when the storm is on the limb, whereas lower frequencies are refracted away from the line of sight. As the planet rotates, the path from the leading edge of the storm to Voyager travels through progressively less ionosphere so that less refraction occurs permitting lower and lower frequencies to be observed. This frequency dependence of SED onset times should occur to some extent for all reappearances and disappearances; however, with the exception of this one occasion near closest approach, this effect is not observed. Since the storm system rotates every 10h 10m, the angular velocity is such that in twenty minutes the storm has moved off the limb by nearly 12 degrees. This is enough to permit even the lowest frequencies (4 MHz) to be observed and corresponds to an onset drift rate of about 1.5 MHz per minute. A drift rate this large is not discernable in the SED data due to the sparsity of SED near the reappearance and disappearance times and the complicated, frequency-dependent sensitivity pattern of the PRA instrument. However, during the period near closest approach, the Voyager-1 spacecraft was moving at a rapid enough speed around the planet to nearly match the planetary rotation speed. Thus, the SED source spent a much longer time travelling across the visible face of Saturn than during any other episode, long enough to generate the observed 0.2 MHz per minute onset drift rate. Panel(b) of Fig. 2 shows the location of the storm system some three hours after panel (a). The leading edge of the system has yet to reach the central meridian, whereas normally the center of the storm system would be on the central meridian.

Panel (b) also corresponds to the time when SED are first detected down to 100 kHz, indicating a very low ionospheric electron density. Notice that the leading portion of the storm system is on the dark side of the planet. Radio occultation measurements of electron density in the ionosphere at the dusk terminator show values corresponding to cutoff frequencies of 600 to 800 kHz[9-11]. We propose that these values must drop substantially shortly after sunset so that by one hour after sunset 100 kHz radio emission can propagate to the spacecraft.

Panel (c) shows the view of Saturn 30 min before the disappearance of SED. The storm system has nearly completed one rotation around the planet from panel (a), and its leading edge is already beyond the limb, with the trailing edge rapidly approaching the limb. By now the Voyager spacecraft has moved past local midnight and is receeding from Saturn very nearly radially so that the apparent motion of the trailing edge of the storm is again at full value and no frequency dependence is observed during the disappearance.

In addition to the occultation evidence, SED are consistent with atmospheric storms in at least two other ways. First, the total power radiated in an SED burst can range from 10^7 watts[1] to more than 10^{10} watts[5]. This is within the normal range of power emitted during a terrestrial lightning stroke[15]. Second, we have determined that the SED burst durations are distributed according to an exponential law with an e-folding time of 57 milliseconds for both Voyager data sets. The average duration from this distribution is 57 milliseconds and the median duration is 39 milliseconds. Rustan and Moreau[16] have determined that the average duration of radio emission accompanying terrestrial lightning at 63 MHz is 34 milliseconds.

Discussion

We believe the analysis presented above forms a compelling argument that SED are generated by storms in Saturn's equatorial atmosphere. However, there are still some unanswered questions which will need further analysis. For example, why are there differences in the SED occurrence rate and discreteness of the SED episodes between Voyager-1 and Voyager-2? Why is the storm system observed during the Voyager-1 confined to only 60 degrees in longitude?

If the same storm system was observed during both Voyager encounters, then the system appears to have dispersed and weakened somewhat during the intervening 9 months. Two points in the equatorial region will spread apart during 9 months by about 22 degrees in longitude for each meter per second difference in their velocities, so only a very small latitude extent in the storm system would suffice to disperse the storm. If the SED observed by Voyager-2 are from the same storm system as those detected by Voyager-1, perhaps the system was formed only a short time prior to the Voyager-1 encounter. We note that the sun passed through the Saturnian ring plane in early March of 1980, thus the shadow of the rings on the atmosphere slowly changed from the Northern hemisphere to the Southern hemisphere. Perhaps the subsequent large changes in temperature and accompanying turbulence between sunlit and shadowed portions of the dayside atmosphere are able to trigger storms. If this storm system had its birth at the beginning of March as a single storm, then its longitude dispersion of 60 degrees by the time of the Voyager-1 encounter would imply a velocity spread of only 3 m/sec, corresponding to much less than 1 degree of latitude extent[7].

Of course, it is also entirely possible that the SED observed during the Voyager-2 encounter are from a different storm system than that observed by Voyager-1. This would imply that a given storm system has a lifetime longer than the several days of an encounter period, but shorter than the 9 months between encounters.

In either case, it is clear that the PRA observations of SED have contributed unexpectedly to the study of Saturn's atmosphere and ionosphere. Our proposed storm model for the source of SED explains the occurrence pattern and frequency-dependence of SED, and does not invoke exotic or unexplained physical phenomena required by the ring source theories[3-5].

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FIGURE CAPTIONS

Fig. 1. Comparison of observed and predicted recurrence patterns for the five SED episodes centered on Voyager 1 closest approach. Panel (a) shows schematically the times and frequencies where SED were dete_ted (black) and undetected (white) by Voyager 1. Before and almost up to the time of closest approach (CA) no SED are seen below about 4 MHz. After CA, SED are regularly seen down to and even below 100 kHz. Panels (b), (c), and (d) compare the predicted recurrence patterns for a 60 deg wide atmospheric storm system, a single (point source) atmospheric storm, and a point source in the rings, respectively. The agreement between the observed and predicted start/stop times for the 60 deg wide surface storm (b) is clear. Note especially the coincidence between start and stop times in the case of the episode centered on CA, which lasts ~ 3 hrs longer than any other episode. The single-storm model (c) consistently predicts shorter episodes than those observed by ~2 hrs, and the ring source model (d) consistently predicts longer episodes by ~2 hrs.

Fig. 2 Voyager 1 trajectory past Saturn is snown projected into the equatorial plane. The shaded globes show the planetary aspect and SED source location as viewed by Voyager 1 at three times near closest approach. On day 317 at 1950 SCET, the source reappears on the west limb of the planet, marking the onset of the third episode in Fig. 1. At 2100 SCET (panel (a)), the leading edge of the source is about 30 deg beyond the west limb; at 0000 SCET (b), the leading edge is about 50 deg beyond the limb and well into the nightside hemisphere, permitting escape of very low frequency (<1 MHz) SED; by 0600 SCET (c), the trailing edge of the source is near the eastern limb, close to disappearing beyond the spacecraft horizon. AT 0625 SCET the episode ends as the source disappears from Voyager's view.

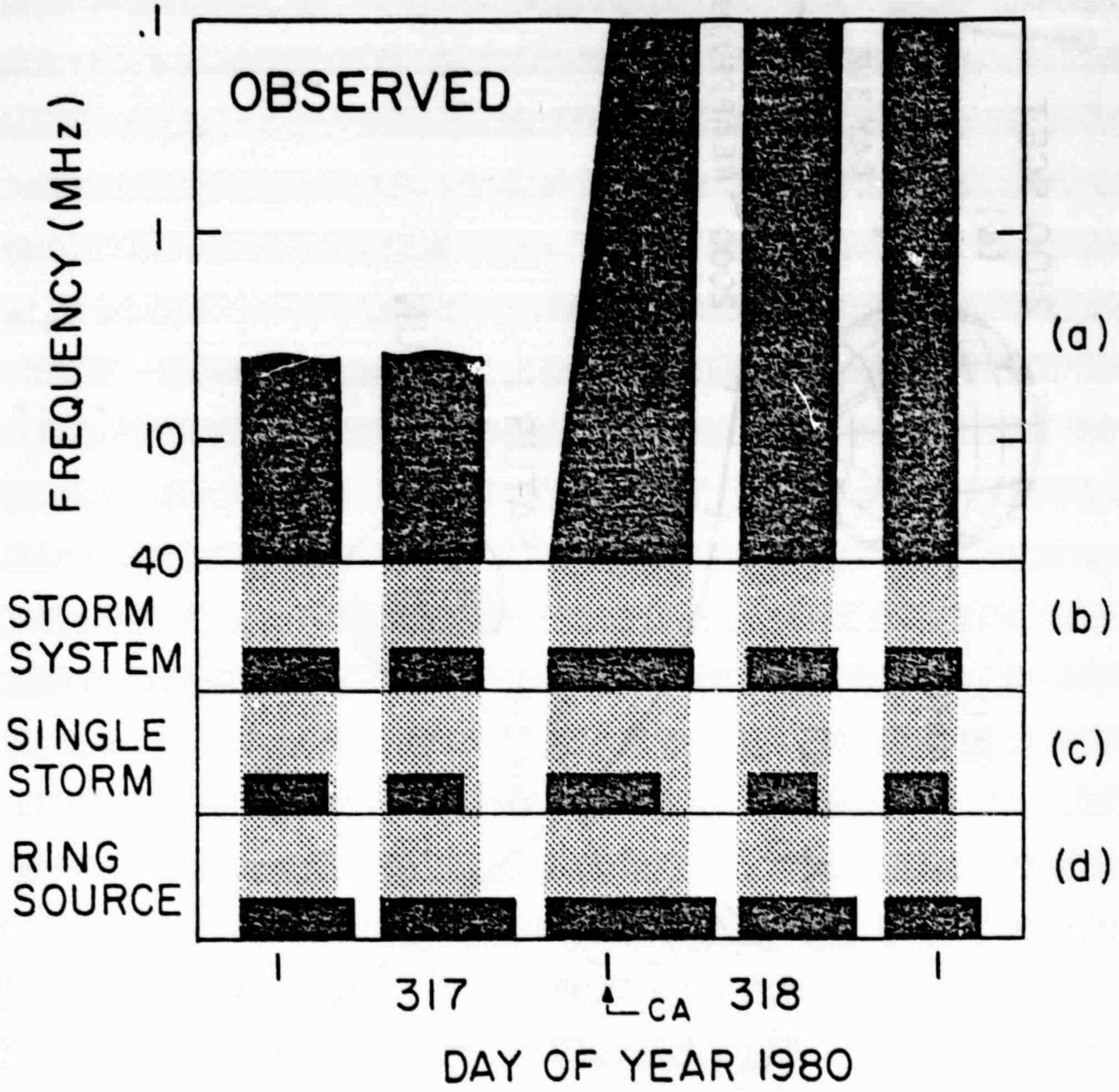
OBSERVED
FREQUENCY (MHz)
.1
1
10
40
(a)
STORM SYSTEM
(b)
SINGLE STORM
(c)
RING SOURCE
(d)
317
CA
318
DAY OF YEAR 1980

Figure 1

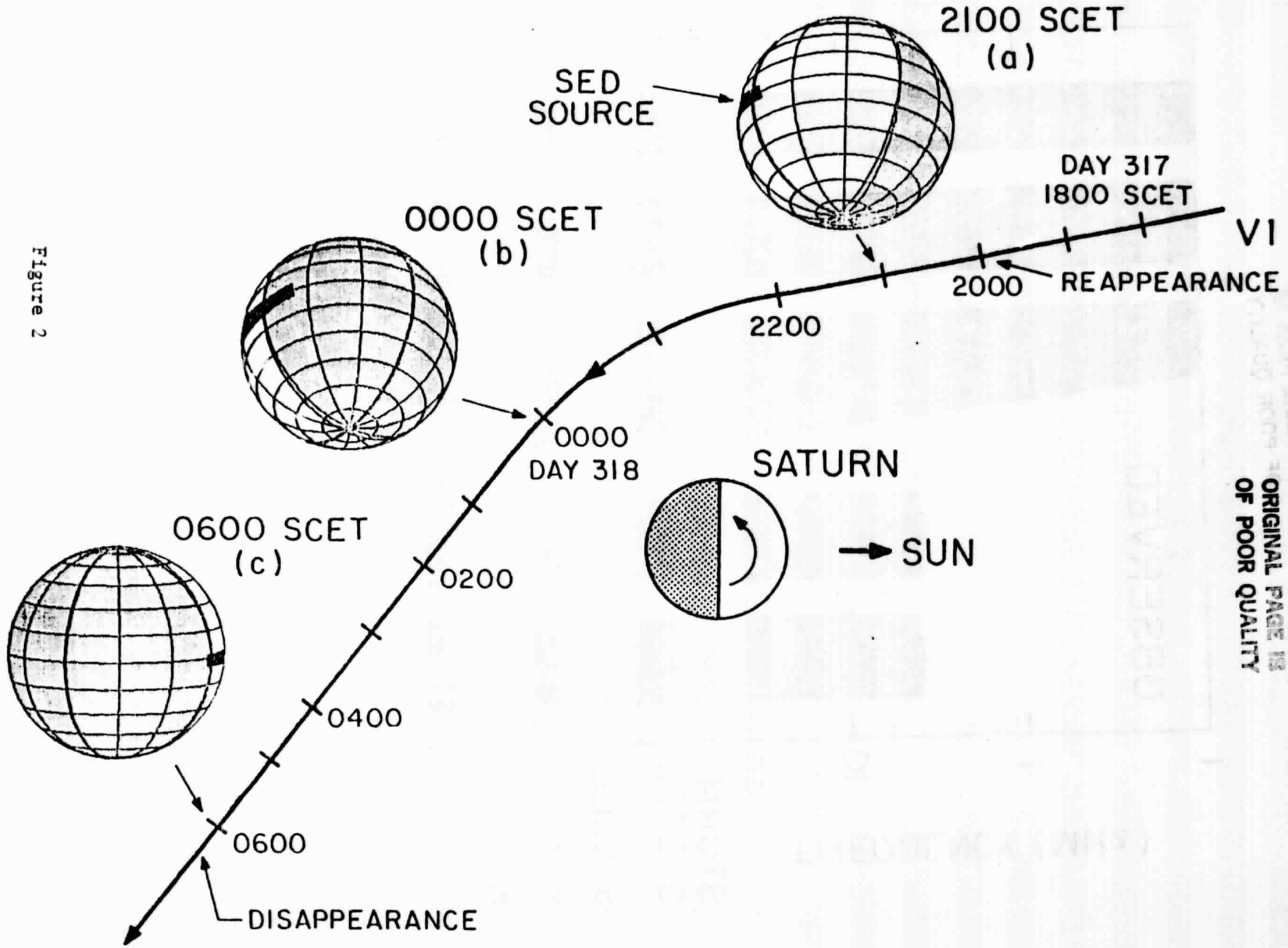
2100 SCET
(a)
SED
SOURCE
DAY 317
1800 SCET
V1
0000 SCET
(b)
REAPPEARANCE
2000
2200
0000
DAY 318
SATURN
0600 SCET
(c)
SUN
0200
0400
0600
DISAPPEARANCE

Figure 2