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Department of Physics and Astronomy

THE UNIVERSITY OF IOWA

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DIRECT DETECTION

OF THE ASYMMETRIC INJECTION

OF EXTRATERRESTRIAL 'RING CURRENT' PROTONS

INTO THE OUTER RADIATION ZONE*

by

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Abstract

Measurements of the spatial distributions and temporal variations of the extraterrestrial 'ring current' proton intensities near the magnetic equator during selected phases of two moderate magnetic storms on 9 July and 8 September 1966 provide direct evidence of asymmetric injection of these proton intensities deep into the outer radiation zone during the early development of the latter magnetic storm. Injection of these low-energy protons ($5 \lesssim E \lesssim 50$ keV) into the evening-midnight quadrant of the outer radiation zone to L-shells $\simeq 3.5$ was accompanied by a substantial polar magnetic substorm observed during similar local times. However, no increases of proton intensities at levels above those typical of the 'quiescent ring current' centered at $L \sim 6.5$ were yet observed several hours later near local noon. Several implications concerning the origin and motions of this plasma during the early development phase of the magnetic storm are discussed.

I. Introduction

Recently, direct measurements of the inflation of the distant geomagnetic field [Cahill, 1966] and of the low-energy proton distribution which dominantly provides the energy for this distortion [Frank, 1967a] have firmly established the large decreases of magnetic field intensity observed with ground-based magnetometers at low and middle latitudes during geomagnetic storms as the signature of a large and variable low-energy charged particle zone encircling the earth, i.e., the 'extraterrestrial ring current'. Ground-based observations [Akasofu and Chapman, 1964] and *in situ* measurements within the outer radiation zone [Cahill, 1968] of the distortions of the geomagnetic field as functions of local time during the early development of magnetic storms are generally interpreted as requiring the injection of 'ring current' proton intensities into the evening sector of the outer radiation zone. Heretofore the only direct observations of a local time asymmetry of the low-energy proton ($5 \lesssim E \lesssim 50$ keV) distributions near the magnetic equator were reported for periods of relative magnetic quiescence [Frank, 1969a]. These quiescent proton intensities are centered at $L \simeq 6.5$ and reach maximum intensities over a range of local times extending from local afternoon to midnight. This local-time range spans the periods of decreases in magnetic field intensities observed with a magnetometer carried on a geostationary satellite at 6.6 R_E (R_E, earth radii) geocentric radial distance [Cummings and Coleman, 1968]. The position of a geostationary satellite is located near the center of the quiet-time extraterrestrial ring current. Corresponding proton ($5 \lesssim E \lesssim 50$ keV) energy densities observed at this location are sufficient to account for these decreases of magnetic field intensities [cf Frank, 1967a; Frank and Owens, 1969]. Our present purpose is to communicate first direct observations of the asymmetric injection of low-energy protons deep into the outer radiation zone during the early development of a geomagnetic storm.

II. Instrumentation

Measurements of the differential energy spectrums of electron and proton intensities, separately, over the energy range 100 eV $\lesssim$ E $\lesssim$ 50 keV were obtained with a sensitive electrostatic analyzer array on board the earth-satellite OGO 3. These electrostatic analyzers, code-named 'LEPEDEA', and the spacecraft have been discussed previously [Frank, 1967b, c; Frank, Stanley, Gabel, Enemark, Randall and Henderson, 1966; Frank, Henderson and Swisher, 1969]. Among the mentionable features of the satellite orbit pertinent to the discussion herein are an orbital period ~ 2 days, initial perigee altitude of several hundred kilometers and an apogee ~ 20 R_E geocentric radial distance. The inclination of the orbit was 31°, and corresponding typical magnetic latitudes of the spacecraft trajectory through the outer radiation zone were ~ 0° to 20° and 20° to 40° for the inbound and outbound passes, respectively. Two periods of observations are included in the present study, early July and early September 1966. The only significant difference in spacecraft operations for these two periods arises from the malfunction of the satellite attitude control system on 23 July 1966 [see Frank, 1967b]. After this date the spacecraft became a spin-stabilized observational platform with the fields of view of one pair of electrostatic analyzers, LEPEDEA 'A', directed parallel to the spin axis, the second pair of fields of view (LEPEDEA 'B') directed perpendicular to this spin axis. Prior to the failure of this attitude control system, the spacecraft body axes were slaved to predetermined directions referenced to the sun and earth directions as seen from the spacecraft and to the satellite orbital plane. The present study utilizes a comparison of measurements of proton directional intensities gained with LEPEDEA 'A' over segments of the satellite trajectory through the outer radiation zone for these two periods. Due to the nearly isotropic angular distributions of these low-energy proton intensities [cf Frank and Owens, 1969] and similar pitch angles viewed with this instrument for both periods of observations, the malfunction of the attitude control system does not obviate direct comparison of proton intensity profiles as functions of shell parameter L for inbound and outbound segments of the trajectory. Typical equatorial pitch angles sampled with LEPEDEA 'A' over $3 \leq L \leq 8$ were 50° to 90° and 20° to 50° for inbound and outbound passes, respectively [cf Frank, 1967a].

III. Observations

The usually difficult task of separating a local-time dependence of the distribution of low-energy protons from temporal, spatial and latitudinal variations within the outer radiation zone for observations with a satellite in a highly eccentric orbit was facilitated in the present study by a fortuitous set of observational conditions. The satellite trajectories through the outer radiation zone as functions of L and local time (geocentric) are summarized in Figure 1 for the two periods of interest in early July and early September 1966. Since the orbital period is closely 2 days, successive trajectories do not largely differ in magnetic latitude or local time at a given L-value (i.e., coordinates for outer zone passes on 7, 9 and 11 July do not significantly differ). Corresponding $D_{ST}(H)$ hourly values are also provided for the two periods of interest at the upper left-hand corner of Figure 1. Moderate magnetic storms occurred on 9 July and 8 September. Four 'snapshots', inbound-outbound profiles of proton ($31 \leq E \leq 49$ keV) intensities as functions of L, are presented in Figure 1 for four phases of geomagnetic storms: pre-storm or quiescent (1), early development phase (3), main phase (4), and recovery phase (2). The times of these four 'snapshots' are also indicated in the $D_{ST}(H)$ plots in Figure 1. The only significant differences in the coordinates for each of these four snapshots of proton intensities, other than time, are the local times at a given L-value. For example, at L = 5 the position of the satellite lies near local evening and local noon for outbound passes in early July (snapshots 1, 2 and 4) and in early September (snapshot 3), respectively. Magnetic latitudes λ_m for a given L-value are similar for each snapshot and are indicated in Figure 1 for L = 5. The observations of the extraterrestrial ring current protons during the magnetic storm of early July (snapshots 1, 2 and 4) have been discussed previously [Frank, 1967a]. Proton ($31 \leq E \leq 49$ keV) directional intensities, protons $(cm^2\text{-sec-sr})^{-1}$, for these three snapshots for inbound segments (closed circles) and the following outbound passes (open circles) are displayed in Figure 1. The intensity scales are linear and identical for all snapshots shown in Figure 3 to promote direct comparison of intensities. Typically, proton directional intensities at a given L-value for inbound passes are larger by factors of ~ 2 to 3 than corresponding intensities observed during the outbound pass. This difference is principally due to the fact that LEPEDEA 'A' samples larger equatorial pitch angles during inbound passes when compared to equatorial pitch angles scanned on the outbound passes at a given L-value and that the angular distributions of these proton intensities are characterized by maximum intensities at pitch angles

$\alpha_o = 90°$ [Frank, 1967a; Frank and Owens, 1969]. Hence, with no significant local-time dependence of the distribution of 'ring current' proton intensities, typical ratios of intensities observed on the same L-shell for pairs of inbound (j_i) and outbound (j_o) passes are $j_i/j_o \simeq 2$-3 in the evening-midnight quadrant of the outer radiation zone during a geomagnetic storm. However, the snapshot (3) of outer zone proton intensities during the early development phase of the geomagnetic storm on 8 September reveals that the proton distributions have penetrated to $L \simeq 3.5$ on the inbound pass (local evening) with maximum proton ($31 \leq E \leq 49$ keV) intensities, 5×10^7 $(cm^2\text{-sec-sr})^{-1}$, positioned at $L \simeq 5$ while at the same L-shell on the following outbound pass (local noon), several hours later, no recognizable departures from typical 'quiet-time' proton intensities were observed. The proton intensities over $3.5 \lesssim L \lesssim 5.0$ observed near local evening exceeded those observed in the vicinity of local noon on these L-shells by factors $\gtrsim 10$. Note that the profile of proton intensities as functions of L for the early development phase of the storm near local evening (snapshot 3, closed circles) is remarkably similar to the main-phase profiles for the earlier storm shown as snapshot 4 in the same sector of the outer radiation zone. In fact, if the proton distribution observed during the inbound pass had been axially symmetric the corresponding $D_{ST}(H)$ decrease would have been

$\sim -35\gamma$ (refer to Frank [1967a] for details of this calculation). The maximum excursion of the $D_{ST}(H)$ values from the preceding 8-hour average was $\pm 5\gamma$. The above fortuitous series of observational conditions provide first direct measurements of the asymmetric injection of storm-time 'ring current' protons into the evening sector of the outer radiation zone during the early development phase of a geomagnetic storm.

IV. Discussion

Direct observations of the asymmetric penetration of ring current protons into the evening sector of the outer radiation zone during the early development phase of a moderate geomagnetic storm on 8 September 1966 have been reported here. The proton ($31 \leq E \leq 49$ keV) intensities at $3.5 \lesssim L \lesssim 5$ near the magnetic equator and local evening were larger by factors of $\gtrsim 10$ than intensities observed on these L-shells near local noon several hours later (refer to Figure 1). Near local noon proton intensities were similar to those usually observed for the 'quiet-time' extraterrestrial ring current centered at $L \simeq 6.5$ [cf Frank and Owens, 1969; Swisher and Frank, 1968]. These large enhancements of proton ($5 \lesssim E \lesssim 50$ keV) intensities on L-shells $\lesssim 4.5$ near the magnetic equator and near the local evening-midnight quadrant of the outer radiation zone are apparently always associated with a main-phase geomagnetic storm [cf Frank, 1967a; Frank and Owens, 1969]. The present direct observations of the asymmetric injection of ring current protons into the evening sector of the outer radiation zone during the early development phase of a geomagnetic storm and of the presence of large intensities of extraterrestrial ring-current protons deep within the outer radiation zone hours before the signature of this proton distribution can be clearly discerned in the $D_{ST}(H)$-versus-time profiles (refer to Figure 1, snapshot 3) are in direct agreement with the conclusions recently inferred from in situ measurements of the distortion of the distant geomagnetic field with a satellite-borne magnetometer [Cahill, 1968]. The above observational evidences of the presence of the storm-time ring current in its early development stages several hours prior to the main-phase decrease in the $D_{ST}(H)$-versus-time profiles support the suggestion that the enhancements of extraterrestrial ring-current proton ($5 \lesssim E \lesssim 50$ keV) intensities can be attributed to the large increases of solar proton ($5 \lesssim E \lesssim 50$ keV) intensities recently observed in the vicinity of the earth prior to and during the development of main-phase geomagnetic storms [Frank, 1969b]. In fact the great variety of main-phase magnetic storms (amplitudes, rate of development, multiple storms, etc.) may possibly be accounted for as primarily the signature of the source, the interplanetary proton ($5 \lesssim E \lesssim 50$ keV) intensities in the vicinity of the earth.

It is of interest here to compare briefly the above observations of asymmetric injection of ring current proton intensities into the evening sector of the outer radiation zone and the simultaneous signatures of magnetic activity recorded at several ground-based magnetic observatories located at auroral latitudes and at selected local times. Magnetograms for the period 00:00 to 09:00 U.T. on 8 September 1966 for stations located at College, Great Whale River and Kiruna are summarized in Figure 2. The observations of low-energy protons on the inbound (local evening) and outbound (local noon) segments of the satellite trajectory at L = 5 were obtained at 03:51 and 06:51 U.T., respectively (refer to snapshot 3, 8 September, Figure 1). The corresponding local times for these inbound and outbound measurements are indicated at each magnetogram included in Figure 2. The three magnetic observatories are located in the local-time quadrants noon-evening (College), evening-midnight (Great Whale River) and midnight-morning (Kiruna) during snapshot 3 of Figure 1. At L = 5 the geocentric local times of the satellite positions were 19:45 and 12:55 for the inbound and outbound passes, respectively. Cursory examination of these magnetograms displayed in Figure 2 shows that large negative bays, $\sim -500\gamma$ amplitude, were in progress at Great Whale River (local evening-midnight) during the segment of the satellite trajectory through the outer radiation zone from L = 5 inbound through perigee to L = 5 outbound while only relatively small fluctuations of magnetic field intensities $\lesssim \pm 50\gamma$, are evident at College (local noon-evening) and Kiruna (local midnight-morning). These ground-based observations of magnetic activity appear to directly reflect the presently reported observations of the asymmetric penetration of ring current protons into the evening sector of the outer radiation zone. The reader is referred to Akasofu [1966] for a survey of ground-based measurements of the asymmetric development of polar magnetic substorms and related phenomena. A broad survey of many of these 'snapshots' of low-energy proton intensities in the distant magnetosphere and corresponding auroral magnetograms is currently being undertaken and will soon be published.

The present observation of a distribution of low-energy protons similar to that typically observed during the main phase of magnetic storms with regard to spectrum, intensities and location deep within the outer radiation zone but differing in its asymmetric confinement to the evening sector of the outer radiation zone and its occurrence during the early development phase of a magnetic storm (in fact, hours before a clear decrease in $D_{ST}(H)$ is discernible) raises immediate queries at to its motion in the magnetosphere. The time required for a 50-keV proton to gradient-drift from $L = 5$ at local evening to $L = 5$ at local noon (inbound and outbound passes, respectively,) in a dipole magnetic field with equatorial pitch angle $\alpha_o = 90°$ is ~ 50 minutes [Lew, 1961]. A more sophisticated calculation for a distorted dipole field does not differ from the above time interval by more than 5 or 10 minutes [Roederer, 1967]. For a 5-keV proton, at the lower energies of the ring-current proton energy spectrum this drift interval between inbound and outbound crossings of the magnetic shell $L = 5$ is ~ 8 hours. No evidence of any increase of proton $(5 \leq E \leq 50$ keV) intensities at $L \lesssim 5$ was observed during the outbound satellite pass ~ 3 hours after observations of greatly enhanced intensities over $3.5 \lesssim L \lesssim 5$ during the preceeding inbound segment. These ring-current proton intensities did not arrive at the local noon sector of the outer radiation zone as would be expected if their motion were principally due to gradient drift. Two possibilities remain: (1) another drift mechanism ($\vec{E} \times \vec{B}$ drifts, diffusive drifts due to fluctuating magnetic and electrostatic fields, etc.) is more important than the expected gradient drift motion and (2) this proton population was lost in some dissipative process within the magnetosphere or passed from the magnetospheric system into the interplanetary medium before arriving at local noon. The present observations are insufficient to evaluate the relative importance of the above two possibilities. However, if the magnetic bay activity restricted to the local evening-midnight hours during the period of satellite observations (see Figure 2) is coarsely interpreted as the signature of these enhanced proton intensities deep within the outer radiation zone then it appears that rapid dissipation of this energy reservoir, $\gtrsim 10^{21}$ ergs in ~ 1 hour, may have prevented this proton distribution from gaining the local noon sector of the outer radiation zone. The magnetospheric and ionospheric current systems associated with the asymmetric development of the extraterrestrial ring current are currently under theoretical consideration [cf Fejer, 1961; Parker, 1966; Cummings and Dessler, 1967;

Akasofu and Meng, 1969]; further experimental evaluation of these current systems is proceeding with broad surveys of the angular and spatial distributions of these proton intensities comprising several hundred of these observational 'snapshots' of proton intensities throughout the outer radiation zone.

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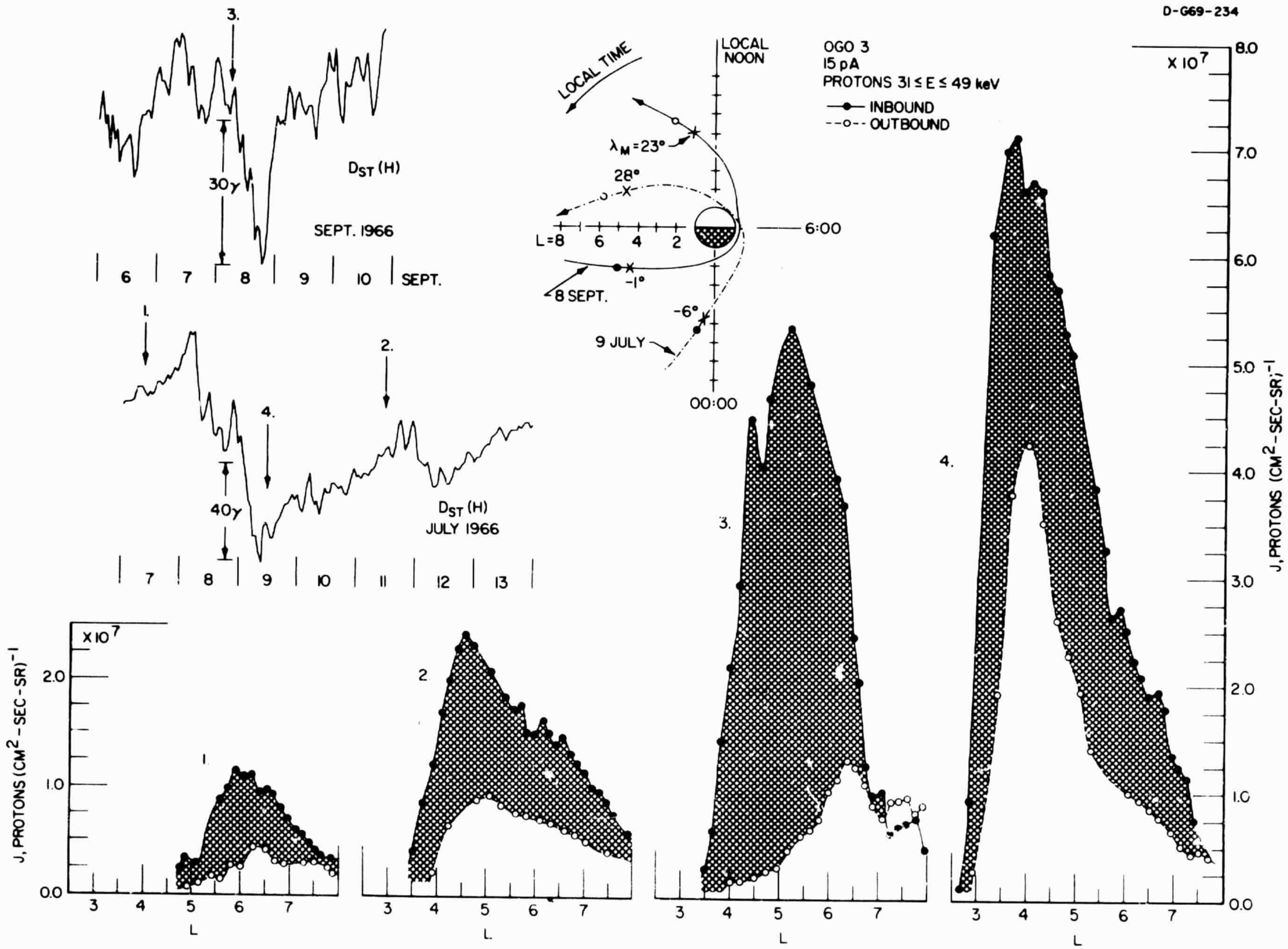
Figure Captions

Figure 1. Proton ($31 \leq E \leq 49$ keV) directional intensities as functions of L during several phases of two moderate geomagnetic storms on 9 July and 8 September 1966. Hourly values of $D_{ST}(H)$ and several useful coordinates for these observations including the OGO-3 trajectory through the outer radiation zone as functions of local time and shell parameter L have also been included in this graphic summary.

Figure 2. Magnetograms for College (magnetic latitude, 64.6°), Great Whale River (66.8°) and Kiruna (65.3°) during the period of observations of low-energy proton intensities in the outer radiation zone on 8 September ('snapshot' 3, Figure 1). Corresponding local times for the inbound and outbound satellite crossings of the magnetic shell $L = 5$ are noted for each magnetic observatory.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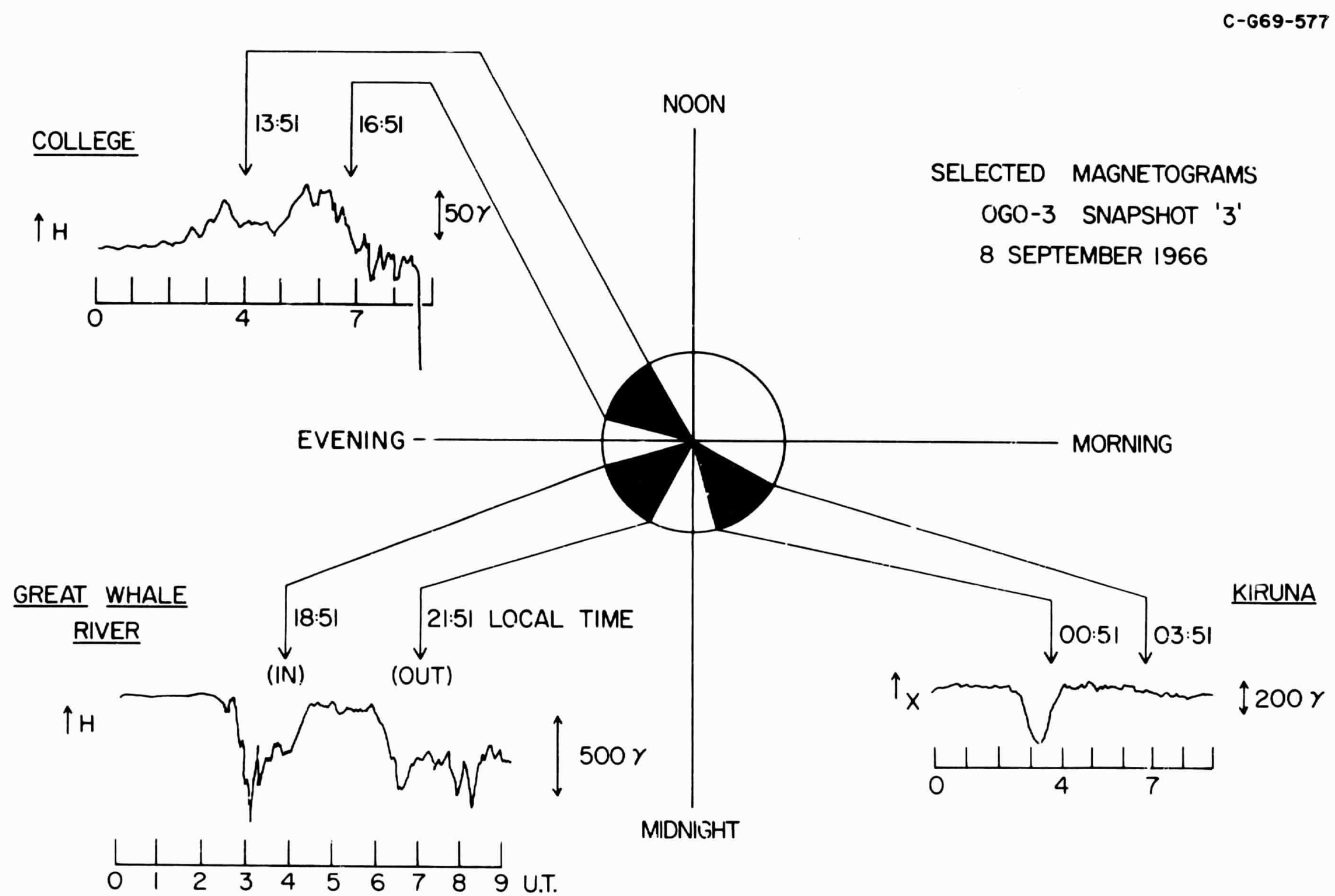
3.
D_{ST} (H)
30γ
SEPT. 1966
6 7 8 9 10 SEPT.
1.
2.
4.
40γ
D_{ST} (H)
JULY 1966
7 8 9 10 11 12 13
LOCAL TIME
LOCAL NOON
$\lambda_M = 23°$
28°
L=8 6 4 2
6:00
8 SEPT.
-1°
-6°
9 JULY
00:00
OGO 3
15 pA
PROTONS 31 ≤ E ≤ 49 keV
INBOUND
OUTBOUND
J, PROTONS $(CM^2-SEC-SR)^{-1}$
X 10^7
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
1
2
3.
4.
3 4 5 6 7
L

Figure 1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SELECTED MAGNETOGRAMS
OGO-3 SNAPSHOT '3'
8 SEPTEMBER 1966
NOON
MIDNIGHT
EVENING
MORNING
COLLEGE
H
13:51
16:51
50γ
0
4
7
GREAT WHALE RIVER
H
18:51
(IN)
21:51 LOCAL TIME
(OUT)
500γ
0 1 2 3 4 5 6 7 8 9 U.T.
KIRUNA
X
00:51
03:51
200γ
0
4
7

Figure 2

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