Pickup proton gyrophase 'bunching at comet P/Grigg-Skjellerup

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Abstract

During the Giotto encounter with comet P/Grigg-Skjellerup, the ion mass spectrometer high intensity spectrometer (IMS-HIS) measured fluxes of ions from about 260,000 before to 86,000 km after closest approach to the comet. Cometary pickup protons were measured both far and also relatively near the comet. Because of the encounter geometry and instrument look direct ion, measurements were made in a very narrow range of pitch angles near 90°. Strong modulation in the detector' countrate was correlated with modulation in the solar wind flow velocity and magnetic field direction (corresponding to the water group pickup ion cyclotron frequency) during the encounter. This correlation indicates that the pitch angle distribution for the pickup protons was very narrow, Furthermore, time variations within this modulation indicate also that the proton distribution was non-gyrotropic. These pickup protons thus appear to be partially trapped in the waves generated by the water group pickup ions.

introduction

During the Giotto spacecraft flyby of comet P/Grigg-Skjellerup (GS) on July 2, 1992, the high-intensity spectrometer (HIS) of the ion mass spectrometer (IMS) instrument [Balsiger et al., 1987] observed a very strong, nearly periodic count rate modulation close to the cornet. Figure 1, taken from our previous study [Goldstein et al. 1994] illustrates this modulation. Because of the geometry of the encounter and the spacecraft spin axis (see Figure 2), the HIS was viewing a relatively small part of velocity space approximate] y perpendicular to the ambient magnetic field. The period of the modulation in the count rate in the detector was similar to the period of the large amplitude Alfvén waves present during the flyby, These waves at the water group (0^+, OH^+, H_20^+, and H_3O^+) ion frequency of -0.011 Hz were most likely generated by the interaction between the solar wind and the picked up water group cometary ions [Neubauer et al., 1993]. Although the HIS was sensitive to both water group ions and protons, the counts in this detector were likely due to the latter cometary pick up ion [Goldstein et al., 1994]. 'J'he modulation in the count rate in Figure 1 was believed to be caused by pick up protons that had a relatively narrow pitch angle distribution (i.e., a ring). The convection of the large amplitude Alfvén waves past the spacecraft caused this ring distribution to sweep back and forth over the IMS/HIS field of view.

In this paper, we describe additional analysis of the IMS/HIS data and show that the pick up protons are not only confined in pitch angle but that they are also confined in gyro-phase. The non-g, yrotropic pick up proton distribution appears to be quasi-trapped in the water-group-generated Alfvén wave.

Data Analysis

To further study the characteristics of the pickup proton distribution, we determine the detailed history of the relatively narrow pitch angles measured by HIS during the encounter, These pitch angles are measured in the solar wind rest frame, It was pointed out in our previous study [Goldstein et al., 1994] that although the IMS/HIS ion data and magnetometer [Neubauer et al., 1993] data were available at 4s resolution, the John stone Plasma Analyzer (JPA) ion flow velocity data had a 128 s time resolution [Johnstone et al., 1993]. Thus the flow velocity, and pitch angle derived from it, would not show variations at the higher water group ion cyclotron frequency. We have therefore estimated the higher frequency velocity variations δV, assuming the relation between velocity and magnetic field fluctuations for Alfvén waves [Belcher and Davis, 197 1]:

$$\frac{\delta V_i}{V_A} = \frac{\delta B_i}{\overline{B}} \bullet \eta, \; i = x, y, z, \qquad (1)$$

where $$" = \frac{\overline{B}}{(4\pi\rho)^{1/2}} \text{ is the Alfvén speed,}$$

$$\delta B_i = B_i - \overline{B}_i,$$

$$\overline{B} = \text{running average,}$$

$$\eta = \sqrt{1 - \left[\left(p_{par} - p_{perp}\right) \Big/ \left(B^2 \big/ 4\pi\right) \right]},$$

and the density is a function of the distance to the comet R

$$\rho \propto R^{-2.11} \qquad \text{[Coates et al., 1993].}$$

Since we do not have a direct measure of the parallel and perpendicular pressures p_{par} and p_{perp}, wc have assumed that the pressure is dominated by water group ions, picked up normal to the magnetic field. Further, the initial pickup distribution is cold, so p_{perp} can be obtained just from the pickup velocity, and $p_{par} = 0$. Figure 3 shows the ion flow velocity calculated From Eq. 1, superimposed on the original, lower time resolution measurements [John stone et al. , 1993].

Using this higher time resolution velocity and the magnetic field measurements, the instantaneous pitch angle viewed by the IMS/I 11S detector in the frame of reference of the solar wind was computed for each 4s spacecraft spin. The results are similar to those previously obtained [Goldstein et al. , 1994] with some relatively minor differences in the pitch angles due to the synthesized higher time resolution velocity measurements. in addition to the pitch angle, the angle between the magnetic field and the direction of the. local pick up (assuming that the ions are picked up with zero velocity in the spacecraft frame) was also computed for each 4 second spin. The difference between the observed pitch angle and this ion injection angle is a measure of how close the IMS/HIS field of view was to the centroid of the pick up distribution. When this difference was small, the sensor was measuring near the centroid of the distribution. Figure 4 shows the pitch angle - injection angle difference as function of the HIS counts/spin over one of the count rate peaks in Figure 1. This Figure demonstrates that the modulation in the count rate was related to the change in the field of view of the detector from a position well away from the centroid of the pick up distribution to a position much nearer the centroid. As the count rate increases to its peak, the pitch angle - injection angle decreases from near 90° to -45° and as the count rate returns to its background level, the pitch angle - injection angle increases to near 90°.

If the proton distribution were a ring-beam in velocity space, then the count rate would be a function of only pitch angle - injection angle. While this difference in angles does order the data, it is clear from Figure 4 that this ordering is not complete. in particular, the increase and decrease in the count rate in the Figure follow different paths so that at the same pitch angle - injection angle, the count rate differs significantly. This difference is an indication that the count rate in the HIS detector depends both on the instantaneous pitch angle - injection angle and on time. The dependence on pitch angle - injection angle indicates that the distribution is confined in pitch angle space. In other words, the distribution is a pick up nng-beam or partially filled shell in velocity space [Goldstein et al., 1994]. The dependence on time indicates that the pickup ring or partially filled shell is also non-gyrotropic. It is this non-gyrotropic nature that we investigate further.

One important quantity of a non-gyrotropic distribution such as the pick up proton distribution at GS is the angle between the gyrating ions and the perpendicular component of the wave electric field, Since $\delta E_\perp$ is perpendicular to $\delta B_\perp$ and the gyrophase of the ions can be estimated from the modulation in the count rate in the HIS detector, the combination of the HIS observations and the magnetic field variations can be used to determine the relationship between the gyrophase angle and the wave electric field as a function of time. This was done previously in a study of gyrophase bunched protons and large amplitude MHD-like waves observed upstream from Earth's bow shock [Fuselier et al., 1986].

Adopting the notation from Fuselier et al. [1986] and Gary et al. [1986], the ion gyrovelocity, $\mathbf{V}_g$, is defined as the component of the ion velocity perpendicular to the ambient magnetic field in the solar wind rest frame. The phase angle, ϕ, is the angle between the perpendicular component of the wave magnetic field and $\mathbf{V}_g$. Beyond the modulation in the HIS count rate, there is no additional information on the pick up proton distribution from the GS encounter. This is unfortunate because if the full distribution had been observed, then the gyrophase could be determined directly from phase space distributions in a manner similar to the procedure used by Fuselier et al. [1986]. Instead, the gyrovelocity is computed from two assumptions. First, it is assumed that the protons are picked up at zero velocity in the spacecraft frame. Second, it is assumed that when the HIS count rate peaks, the pick up protons are oriented along Y.

Figure 5 is a polar plot of the HIS countrate as function of the gyro phase angle for each 4s spin for the interval from 1500:02 to 1507:00 SCET (corresponding to a distance range from 15694 to 9842 km from the comet). Only counts /spin above 80 have been plotted because the assumptions used to compute the gyrovelocity apply only to the peaks in the HIS count rates. It is clear that the peaks above about 90 counts/spin are confined between 90" and 180° in gyrophase angle and the highest count rates are at approximately 135". In other words, the gyrovelocity of the non-gyrotropic proton distribution is at an angle between 0° and 90° (i.e., -45°) from the wave electric field,

Discussion

Figure 4 shows that the periodic peaks in the HIS countrate in Figure 1 are ordered by the instantaneous pitch angle - injection angle of the pickup ion ring. Figure 5 shows that these peaks *are* also ordered by the gyrophase of the ions within this ring. Thus, both conditions must be met in order to produce a peak in the HIS countrate. This double condition is illustrated schematically in Figure 2. This Figure shows the relation between the HIS field of view for protons, the instantaneous wave field vectors $\delta \mathbf{E}_\perp$ and $\delta \mathbf{B}_\perp$, and an ion gyrovelocity vector $\mathbf{V}_g$ corresponding to a pickup ring at 90°. The mean magnetic field points out of the plane of the Figure in this illustration. (During the encounter, the magnetic field was actually mostly in the B_y direction so that the pickup ring would be rotated by 90° and lie in a plane approximately perpendicular to the plane in Figure 2. However, in this illustration the actual orientation of the field is unimportant.)

For the GS encounter, the large amplitude Alfvén waves propagated antiparallel to B [Neubauer et al., 1993], so the wave vectors rotate clockwise in the plane of the Figure. As the wave convects past the spacecraft, the instantaneous orientation of the magnetic field changes from the Z direction and the pickup ring turns in and out of the plane of the Figure (thereby changing the observable pitch angle - injection angle). At the same time, the gyro-velocity vector of the non-gyrotropic pickup ion distribution rotates around this ring. Thus, both the pitch angle - injection angle and ϕ must be near the HIS field of view for the instrument to observe a peak in the countrate.

Gyrophase bunching of pickup ions has previously been studied near earth (e.g., Mauk, 1982 and Fuselier et al., 1986). Mauk described the case of heavy ions (He^+ trapped in the cyclotron waves of a lighter ion (H') and distinguished between the two extremes of "magnetic wave trapping" and "electric phase bunching". The present situation for GS corresponds to Mauk's "electric" case.

Fuselier et al. [1986] have discussed gyrophase bunching of pickup protons upstream of Earth's bow shock. But there are two very important differences in the relation between the pickup proton distributions and large amplitude waves at GS and the proton distributions and waves upstream of Earth's bow shock. First, in Fuselier et al. [1986], the upstream waves were generated by the protons so these waves were in resonance with the particles and could trap them by resonant interaction. At GS, however, the waves were generated by the water group ions and were not in resonance with the picked up protons. The proton cyclotron frequency, in fact, is approximately 16 to 19 times higher than that of water group ions. Second, the waves upstream from Earth's bowshock were generated by a proton distribution with a significant parallel speed component (i.e., a ring beam distribution) and were therefore generated by the right hand resonant ion beam instability. In the case of GS, the magnetic field was nearly perpendicular to the solar wind flow direction near the comet, so the waves generated by the water group ions were left hand polarized A lfvén waves.

It is somewhat surprising that the GS pickup protons should be bunched in phase with a large amplitude Alfvén wave generated by water group pickup ions. A clue to the reason for this quasi-trapping can be found in the relationship between the gyrophase angle and the wave electric field. The rate of work, P, done by the wave field on a gyrating ion of charge q is

$$P = q\,\delta\mathbf{E}_\perp \cdot \mathbf{V}_g\,,$$

and at steady state, when P = O, ϕ = 0° or 180”. When the wave does work on the ion, P > (), and 0°<$<180°. On the other hand, if the ion gives up energy to the wave, P < 0, and 180°> ϕ >360°. We see then, that the gyro phase angle distribution in Fig. 5 indicates that most of the HIS ion peaks occur when the wave does work on the ions. We conclude, therefore, that as the protons are picked up and injected into the flow, the water group frequency Alfvén waves trap these ions in the wave and gyrophase bunch them. Apparently, in the presence of the waves, the new ions are unable to pitch angle or phase scatter easily by their own wave-particle processes. This gives further argument for our previous [Goldstein et al., 1994] identification of these ions as protons, and not water group ions. Water group ions would be found at ϕ between 180° and 360° in a growing Alfvén wave or at 180° after wave saturation. Furthermore, water group ions would be close to resonance with the waves and would surely scatter. Finally, the conclusion above that the waves do work on the particles may be an explanation for the broad energy spectrum observed for these ions [Goldstein et al., 1994].

Acknowledgments

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References

Balsiger et al., The ion mass spectrometer on Giotto, *J. phys. E,* 20,759-767, 1987.

Belcher, J. W. and L. Davis, Jr., Large-amplitude Alfvén waves in the interplanetary medium, *J. Geophys. Res.,* 76, 3534-3563, 1971.

Coates, A. J. et al., Pickup water group ions at comet Grigg-Skjellerup, *Geophys. Res. Lett.*, 20, 483-486, 1983.

Fuselier, S. A. et al., The phase relationship between gyrophase-bunched ions and MHD-like waves, *Geophys. Res. Lett.*, 13, 60-63, 1986.

Gary, S. P., Electromagnetic instabilities and gyrophase-bunched particles, *Phys.* Fluids, 29, 531-535, 1986.

Goldstein, R. et al., Giotto ion mass spectrometer measurements at comet P/Grigg/Skjellerup, *J. Geophs. Res.,* 99, 19255-19265, 1994.

Johnstone, A. D. et al., Observations of the solar wind and cometary ions during the encounter between Giotto and comet P/Grigg-Skjellerup, *Astron. Astrophys.,* 27.?, L1-1.4, 1993.

Mauk, 11. 11., Electromagnetic wave energization of heavy ions by the electric "phase bunching" process, *Geophys. Res. Lett.,* 9, 1163-1166, 1982.

Neubauer, F. M. et al., First results from the Giotto magnetometer experiment during the P/Grigg-Skjellerup encounter, *Astron. Astrophys.,* 268,1.5-1.8, 1993.

Figures

1.1 MS-I II S counts/spin measured during the Giotto flyby of comet P/Grigg-Skjellerup.

2. Schematic illustration of the HIS field of view for protons in the XY plane. In this example, the bulk flow is 200 km/s along -X, and **B** is along +Z. The wave vectors $\delta E_\perp$ and $\delta B_\perp$ in the plane normal to the field are also shown, as is the ion gyro-velocity vector V_g. The Alfvén wave flops the ring in and out of the plane, while at the same time rotating the vectors (clockwise in this view) around the ring, Both the orientation of the plane as well as the gyrovelocity must be "just right" for HI S to measure an appreciable count rate.

3. A comparison of the total ion flow velocity measured by the JPA sensor [Johnstone et al., 1993] and the higher time resolution velocity estimated from the magnetic field variations. See the text for details of the calculation.

4. Dependence of the measured HIS counts/spin on the calculated pitch angle - injection angle difference during the period 1508:17 to 15:09:05 SCET UT, corresponding to one of the peaks shown in Fig. 1. The countrate is ordered by the difference between these angles, but is not solely a function of this angle. This indicates that the distribution must be confined in both pitch angle and gyrophase.

4. Polar plot of HIS counts/spin as function of proton gyrophase angle. These ions appear mostly restricted between 90° and 180°; i.e., they are "gyrophase bunched".

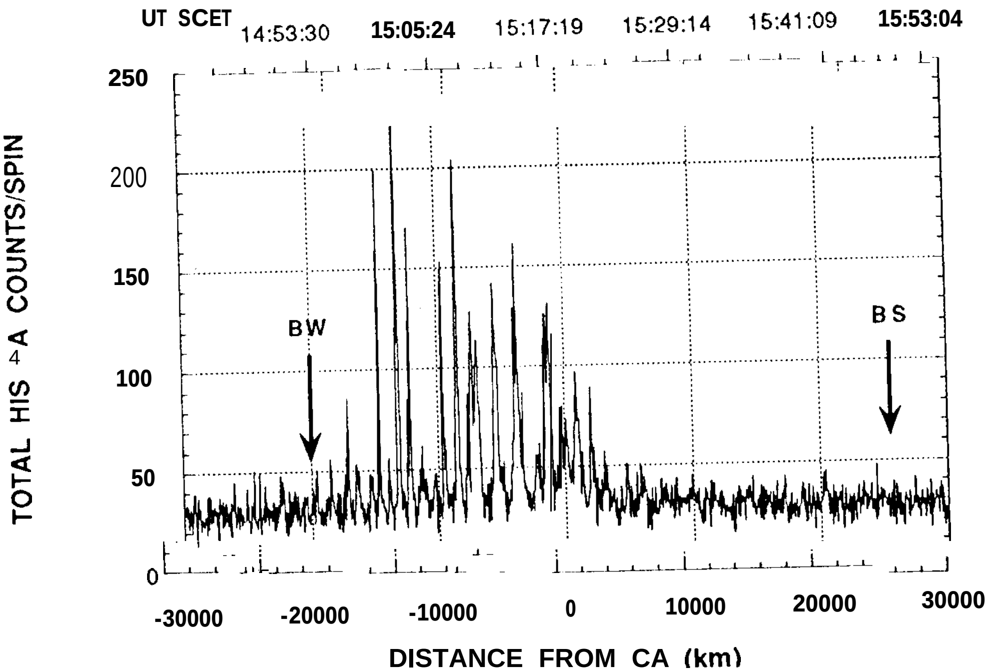

UT SCET
14:53:30
15:05:24
15:17:19
15:29:14
15:41:09
15:53:04
TOTAL HIS 4A COUNTS/SPIN
250
200
150
100
50
0
BW
BS
-30000
-20000
-10000
0
10000
20000
30000
DISTANCE FROM CA (km)

Fig. 1

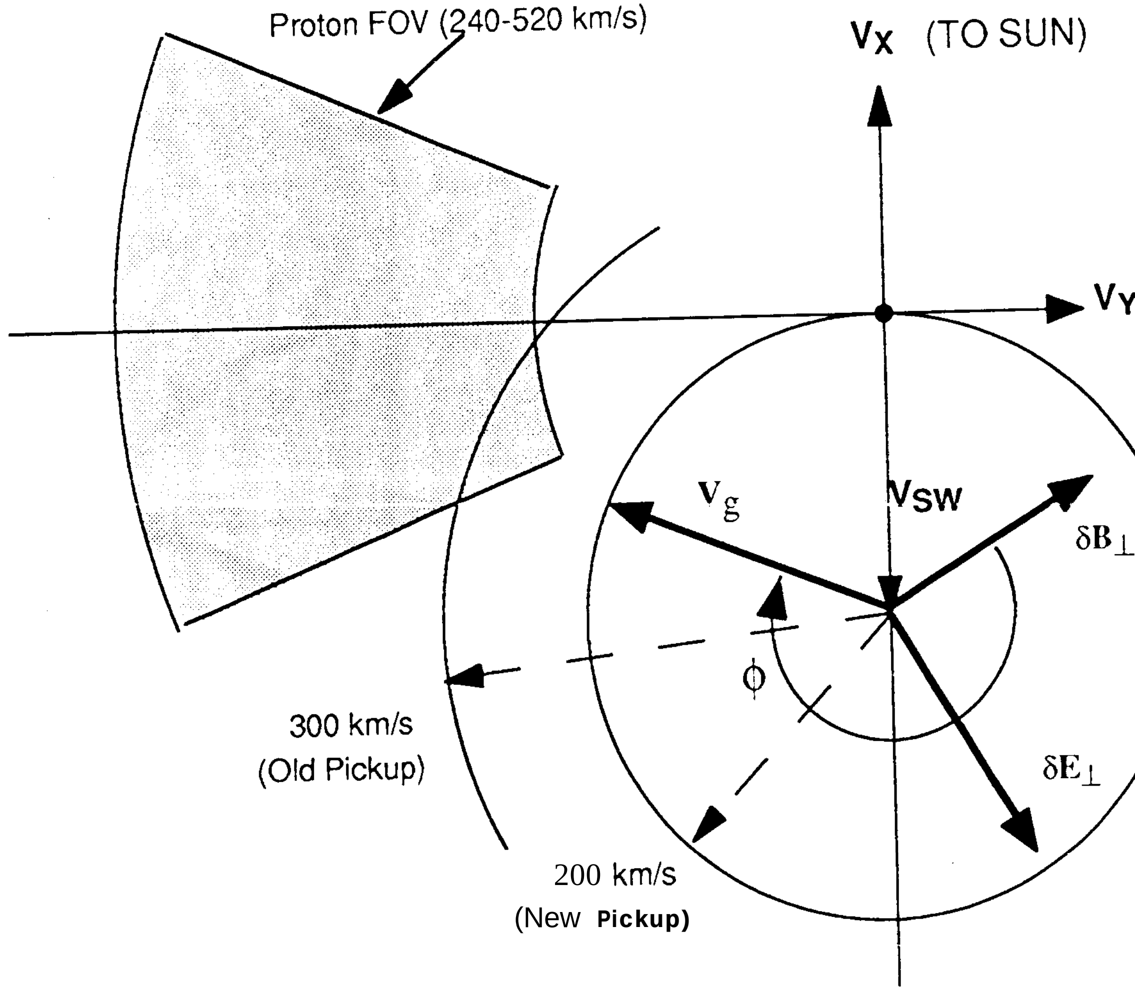

Proton FOV (240-520 km/s)
VX (TO SUN)
VY
Vg
VSW
δB⊥
δE⊥
φ
300 km/s
(Old Pickup)
200 km/s
(New Pickup)

Fig. 2

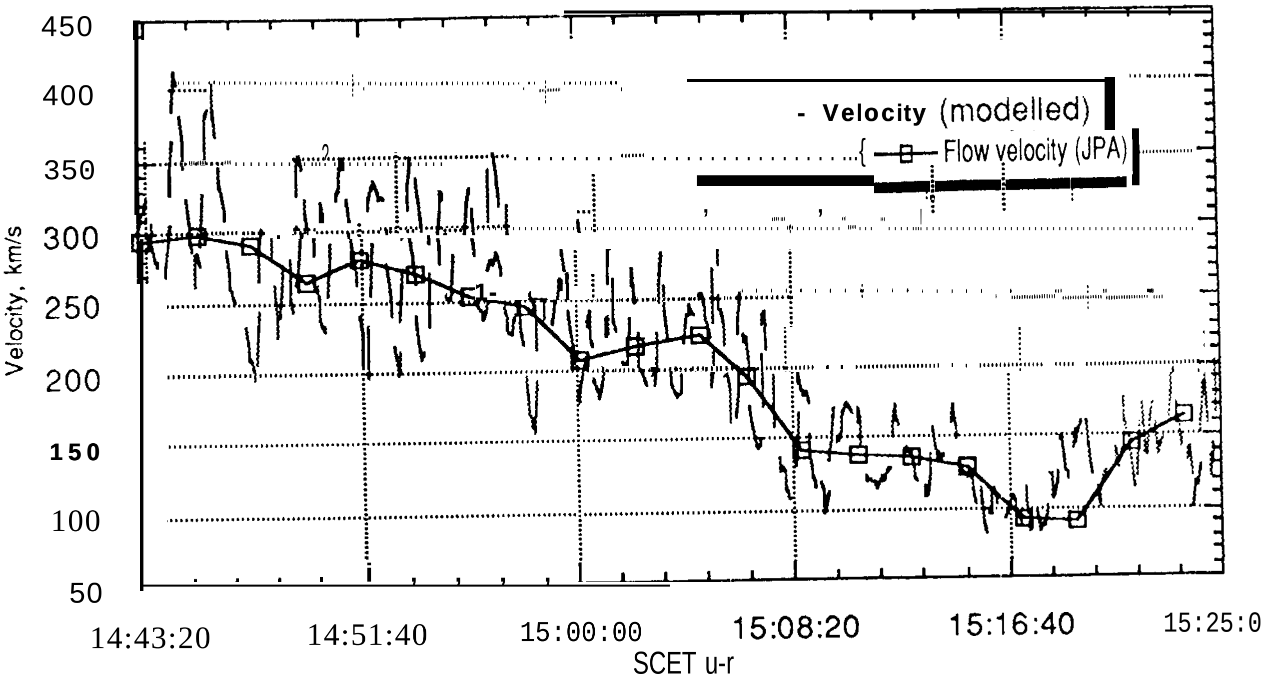

450
400
350
300
250
200
150
100
50
Velocity, km/s
- Velocity (modelled)
Flow velocity (JPA)
14:43:20
14:51:40
15:00:00
15:08:20
15:16:40
15:25:0
SCET u-r

Fig.3

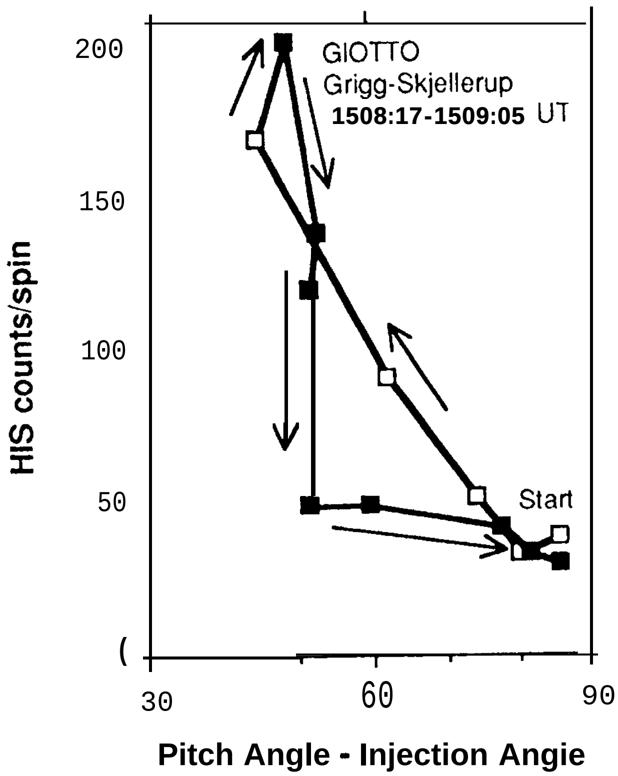
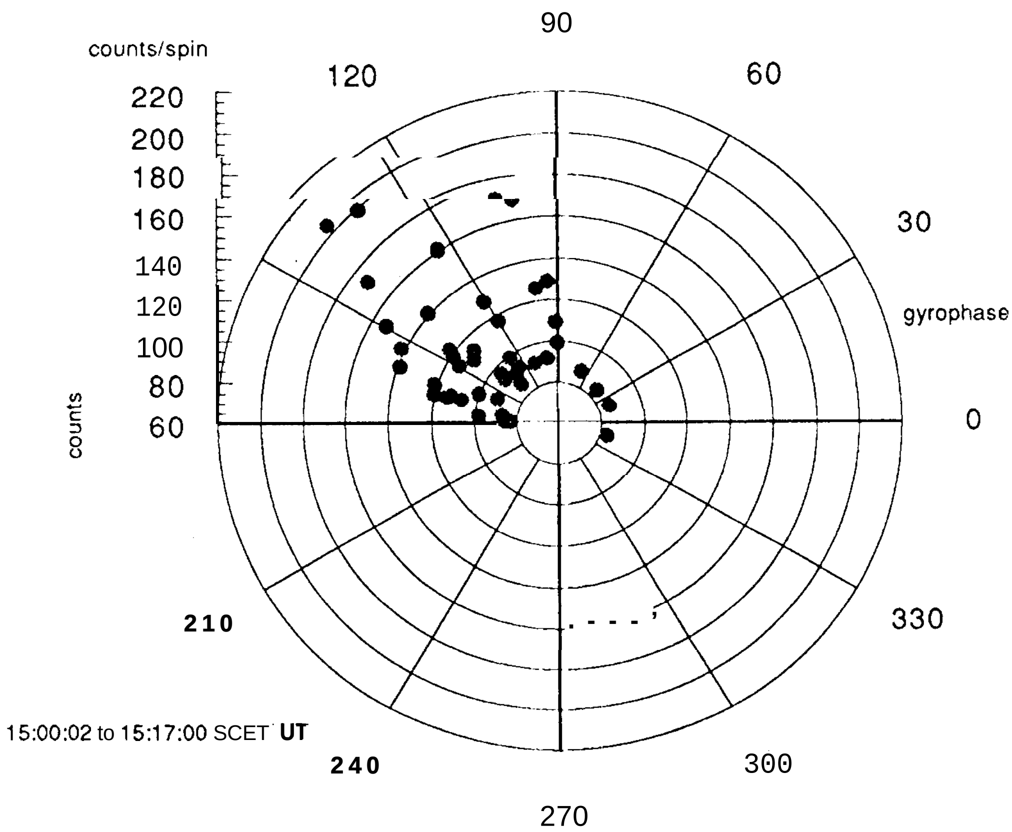

GIOTTO
Grigg-Skjellerup
1508:17-1509:05 UT
Start
HIS counts/spin
200
150
100
50
30
60
90
Pitch Angle - Injection Angie

Fig. 4



90
counts/spin
120
60
220
200
180
160
140
120
100
80
60
counts
30
gyrophase
0
210
330
15:00:02 to 15:17:00 SCET UT
240
300
270

Fig. 5