LARGE SCALE CHANGES IN THE HIGHLY ENERGETIC CHARGED PARTICLES IN THE REGION OF THE IO TORUS

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ABSTRACT

The Galileo star sensor is heavily shielded from penetrating radiation to prevent false counts. Nevertheless in the inner jovian magnetosphere the penetrating radiation appears to be sufficiently strong that significant background counting rates are seen. The morphology and time variation of these background rates are consistent with the hypothesis that they are caused by energetic trapped particles. On the C22 pass through the torus region the count rates were unusually high as if a particularly large disturbance had occurred. We speculate that such disturbances arise at times of rare but intense volcanic activity at Io that causes intense temporal fluctuations in the magnetic field and enhanced radial diffusion and particle energization.

INTRODUCTION

The Galileo orbiter [*Russell*, 1992] entered into jovian orbit on December 7, 1995 after a close flyby of the moon Io whose orbit lies at a jovicentric distance of 5.9 jovian radii. From this pass, that has been termed the J0 pass, until the C20 orbit Galileo stayed outside a distance of 9 R_J. Four gravity-assist passes by Callisto on orbits C20 to C23 gradually lowered perijove beginning in May 1999 and lasting through September, in preparation for the later series of Io encounters (I24, I25, and I27).

The Galileo star sensor provides the data needed to determine the spacecraft attitude [*Birnbaum et al*., 1983]. It is heavily shielded to prevent false star sightings in its photomultiplier tube. Energetic particle hits that can be recognized as such are counted and this background count rate is recorded and telemetered to Earth. On the J0 pass, the background count rate was low until inside the orbit of Io with a dip in the count rate at the orbit of Io supporting the assumed energetic charged particle origin for these counts.

When perijove was lowered in 1999 at first there was no obvious change from the earlier measured fluxes but, when the first large step toward Io took place on the C22 pass, a very large difference with the earlier pass was noted. This is illustrated in Figure 1 that shows the star sensor background counts on the J0 and C22 passes together with the later fluxes measured on C23 and I24. These fluxes are plotted versus the L-value obtained using a dipole field approximation. Inbound and outbound data are shown as are the magnetic latitudes along each pass. No outbound data are available from the J0 pass. Clearly the inbound J0 pass has the lowest counts and the C22 the highest count levels. Until these data were recorded the J0 levels were taken to be the typical background count rates for the inner magnetosphere since measurements on the energetic particle instrument on the probe [*Fischer et al*., 1992] found similar flux levels inside the orbit of Io to those found on earlier missions [*Fischer et al*., 1996; *Mihalov et al*., 2000]. This unexpected change in levels was of much concern to the project operations staff because single event upsets due to radiation belt particles had caused earlier operational problems. Thus the mission proceeded with much caution. The objective of this report is to show that the star sensor background counts are caused by the trapped radiation, to establish what typical levels of these counts are, and to attempt to determine why these count rates vary.

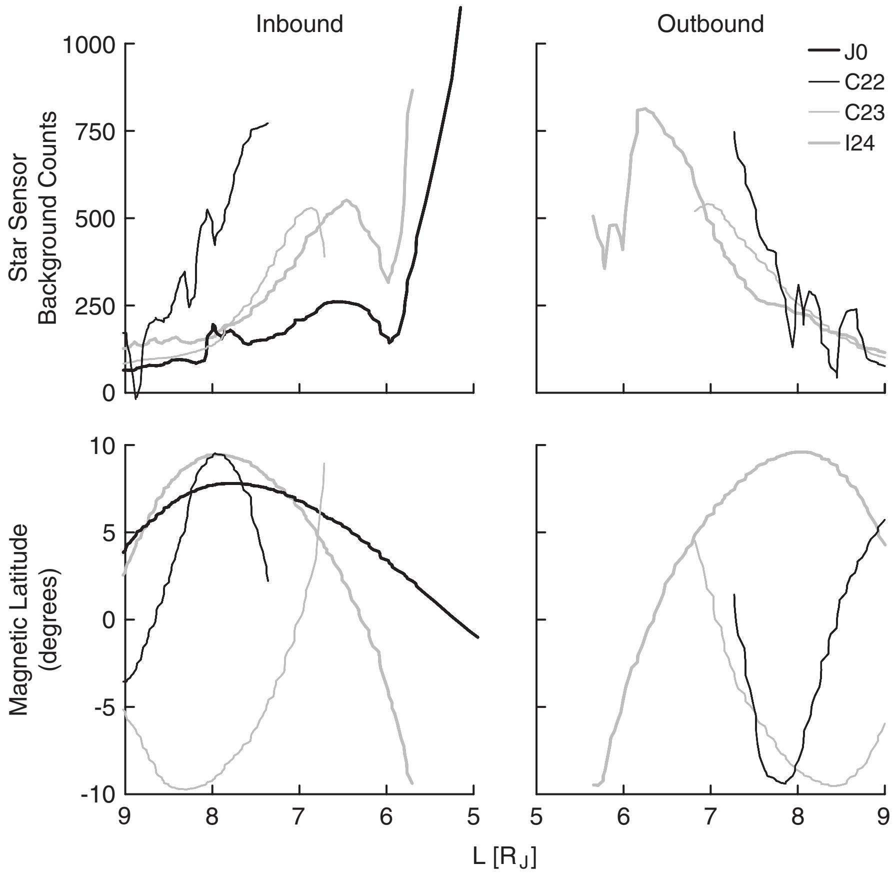

Fig. 1. Background counts of the Galileo star sensor on four passes through the magnetosphere, I0, C22, C23 and I24. Lefthand upper panel shows the inbound rates and the righthand upper panel shows the outbound rates. Counts are plotted versus dipole L-value. Lower panels show the corresponding magnetic latitudes calculated for a dipole moment tilted 9.6^o toward an east longitude of 158^o.

TYPICAL BEHAVIOR

While the J0 and C22 passes were quite different, the next four passes, C23, I24, I25 and E26 all had similar but not identical count rate profiles as shown in Figure 2. The four inbound passes were the most similar with a rise to a maximum count rate of about 500 near an L-value of 7 R_J and a fall to a minimum of about 300 near the Io orbit. Outbound there are some differences between the passes. The I25 pass has generally lower count rates outbound than inbound whereas the I24 pass has generally higher counts outbound than inbound.

Since Galileo orbits Jupiter in its rotational equator and since the magnetic dipole axis is tilted about 9.6^o to the rotational axis, the magnetic latitude of the Galileo spacecraft ranges between -9.6^o and +9.6^o. Trapped energetic particles generally have a pitch angle distribution that is peaked at 90^o and is a minimum along the magnetic field direction. This anisotropy could lead to a reduced count rate off the equator. Examining the magnetic latitude plotted on the bottom panels of Figure 2 we see that on orbit I25 at L=6.5 inbound the magnetic latitude was close to -9.5^o and on the outbound pass it was close to +9.5^o. On I24 just the reverse occurred, the counts outbound were much greater than those inbound at L-values close to Io. At L-values of 6.3 the count rate was close to 500 inbound and 800 outbound both at latitudes near 0^o. Thus in neither of these cases do we attribute the differences in count rates to the pitch angle distribution of energetic charged particles. However, these two examples close to the Io orbit appear to be the exception rather than the rule.

Figure 3 shows the count rate plotted on a log scale as a function of latitude for these four orbits. Smooth curves have been drawn to guide the eye for each L-value. Crosses and exes show the counts near L=9 inbound and outbound. Except for one data point from I25 the rates are quite consistent with a gradual decrease in intensity with increasing pitch angle. Boxes and diamonds show the rates near L=8. Again the rates are consistent with a smoothly varying profile with magnetic latitude as are the rates indicated by triangles at L=7. Near L=6 the rates are not well described by a simple monotonic magnetic latitude variation and we draw a smooth curve with a

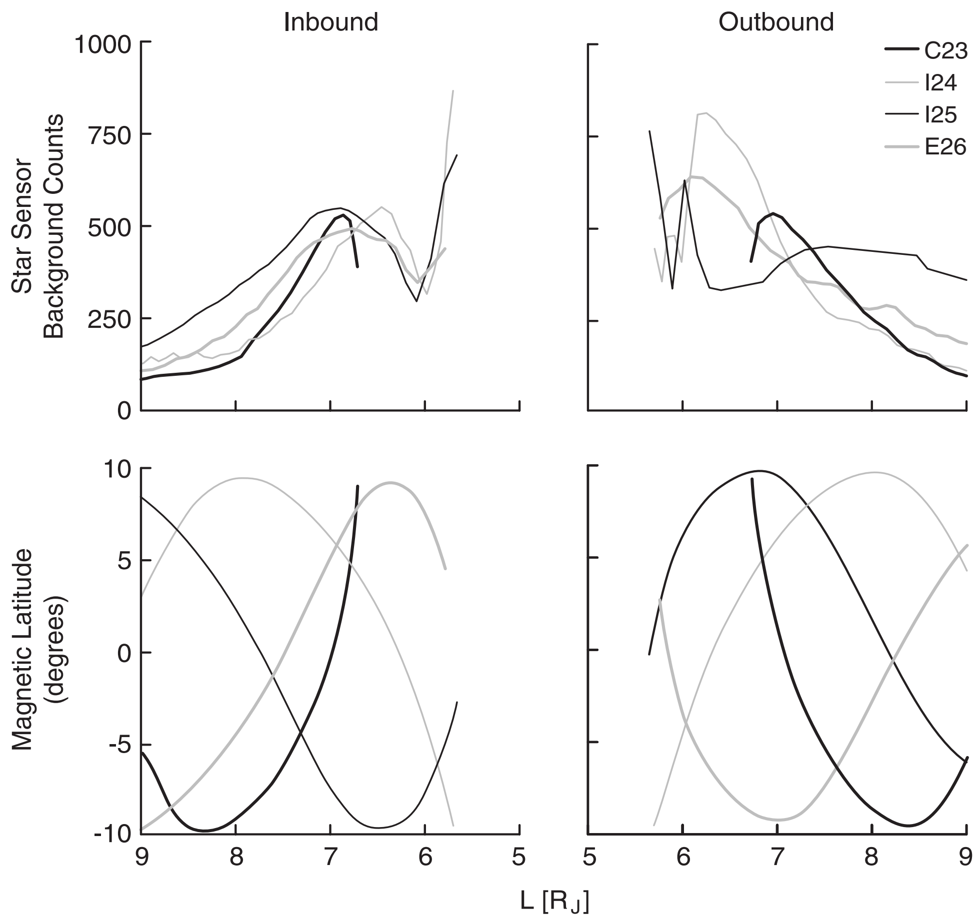

Fig. 2. Background star sensor counts for orbits C23, I24, I25 and E26.

maximum near 5° to approximate the count rate. We will return to this point later. We note that all measurements reported here both inbound and outbound were obtained on the morning side of the jovian magnetosphere between 3 AM and noon. See Figure 2 of Russell et al. [2001a].

PASSES J0 AND C22

Figure 4 shows the background counts for the J0 and C22 passes plotted on top of the smooth "guide" lines of Figure 3. If the fluxes causing these counts were constant then the inverted triangles would fall on or near the line labeled 9. Clearly pass J0 is low and C22 is high. Similarly the upward pointing triangles should lie near the line labeled 8. The J0 point is again low and the two C22 points high. In fact one of the C22 points (at highest latitudes) is at the flux level expected for L=6. The other two points on this diagram are both from the J0 pass: at L=7 where the flux is much lower than the trend in the curves and at L=5 where we have no earlier reference values. From these data it appears that at least outside of Io, the J0 pass was overall much quieter than usual and the C22 pass much more disturbed.

THE ENERGY OF THE PARTICLES CAUSING THE STAR SENSOR BACKGROUND

Since the star sensor is well shielded against penetrating particles it is unlikely that torus energy particles, albeit plentiful, would contribute to the star sensor background. On the other extreme the particles could not be too energetic because their gradient drift velocities would cause them to travel rapidly in azimuth, disperse and populate the entire Io drift shell. Particles with 16 MeV perpendicular energy at Io's orbit will gradient drift at 57 km/s, the corotational velocity of the jovian plasma relative to Io. Electrons drift westward in the jovian magnetosphere and at this energy could remain stationary with respect to Io. Ions would drift with the corotating plasma and in this energy range would quickly encircle the magnetosphere. The fact that on I24 and I25 there are longitudinal asymmetries in the energetic particles responsible for the star sensor background suggests that the responsible particles are drifting only slowly with respect to Io or that the temporal variations in the energetic

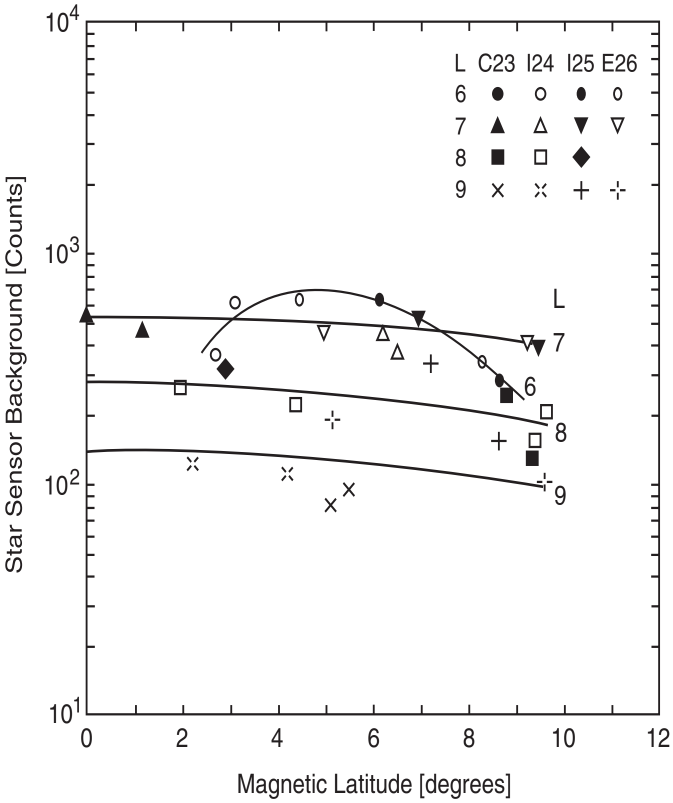

Fig. 3. Star sensor counts versus magnetic latitudes at each of four L-values for orbits C23, I24, I25 and I26. Smooth lines approximating the flux at each L-value have been drawn to guide the eye.

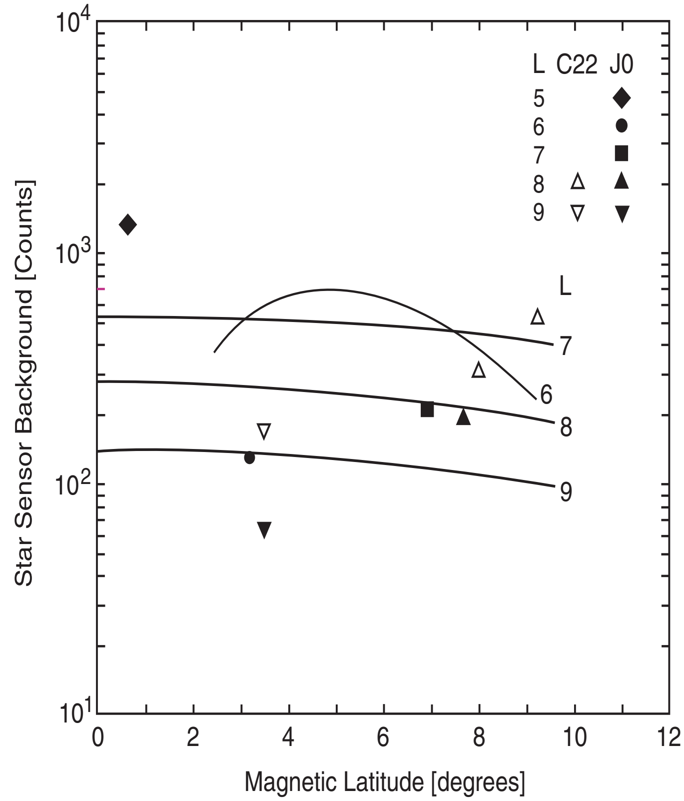

Fig. 4. Star sensor counts versus magnetic latitude at each of four L-inches for pass J0 and C22. The smooth lines drawn for each L-value are the same as shown in Figure 3.

particles are quite frequent. Since the particles must be very energetic to affect the well shielded star sensor we expect the particles to have energies well above an MeV. If they were ions they would rotate in the direction of corotation spread in longitude. If they were electrons much above about 20 MeV they would also spread around the magnetosphere relative to Io relatively quickly but in the opposite direction. Thus electrons in the neighborhood of 10-15 MeV seem the most likely candidates for the causative particles. Moreover, electron fluxes in this energy range vary in radial distances like the star sensor background does. For E<3 MeV the radial profile is too flat and for E>35 MeV the dip at Io is too small [*Fillius*, 1976; *Russell and Walker*, 1995]. The Galileo orbiter carries an energetic particle detector that includes channels in this energy range [*Williams et al*., 1992] and a heavy element monitor [*Garrard et al*., 1992] but to date no results have been reported for the C22 and following orbits [personal communication, *D. J. Williams*, 1999].

AN ASSOCIATION WITH VOLCANISM?

Volcanic activity on Io has been monitored during 1999 by Robert Howell and John Spencer and the results of this monitoring reported on their web pages: http://www.lowell.edu/users/ijw and http://faraday.uwyd.edu/physics.Astronomy/facult/rhowell/io_1999.htm. The first successful observations obtained on May 23 show a relatively inactive Io. An eruption was detected by John Spencer on June 22 and confirmed by Bob Howell on June 29 and July 1 but the source had faded considerably by then. Observations on July 8 (Spencer) and July 10 (Howell) show that the eruption had faded to nearly the brightness of other sources on Io. Observations on July 24 and 26 show a relatively inactive Io. Observations on August 2 show that a major outburst was underway at a site near 71° W and 9° N. The outburst had faded to an undetectable level by August 9. Occultation data from September through November show that Loki is the dominant source at 10 microns with brightening continuing through I24 on October 11, with slightly greater emission in November. It is tempting to ascribe the spectacular count rate increase seen on the C22 pass of August 12 to magnetospheric activity stimulated by the August 2 through 9 volcanic outburst. The inbound and outbound passes exhibit some asymmetry which could indicate that the flux has not had time to spread uniformly to all longitudes but it is sufficiently enhanced at all longitudes that this event must have been prolonged (or very energetic).

AN ASSOCIATION WITH MAGNETOSPHERIC ACTIVITY?

In an accompanying paper we have developed an index of the stretching of the magnetosphere due to the current in the magnetodisk [*Russell et al*., 2001b]. Figure 6 of that paper shows the index for each orbit of Galileo when it could be calculated. When the index is negative the field in the inner magnetosphere is weaker than usual and the magnetodisk should be stronger. The index certainly shows that the magnetodisk current varies but it shows no correlation with the C22 event in the star sensor. This lack of correlation is consistent with our above hypothesis that the low energy (torus) plasma does not directly cause the star sensor background variations, but we cannot rule out that changes in the highly energetic particles have occurred that make at most small changes in the currents circling Jupiter.

DISCUSSION

Particles in the Earth's magnetosphere at the energies we suspect are responsible for the star sensor background are energized as they diffuse radially inward in the Earth's magnetic field. In the case of the Earth the diffusion is thought to be induced by the variation in the external solar wind pressure and the magnetospheric electric field induced by fluctuations in the interplanetary magnetic field through reconnection with the Earth's magnetic field. In the jovian magnetosphere the Io torus plasma provides the seed population for the energetic particles but an energization step is needed before diffusion can result in the observed radial profiles of energetic particles [*Barbosa et al*., 1984]. This energization and diffusion may be induced by Io. If our hypothesized association with Io's varying volcanism is correct, then this additional atmospheric column density may have increased the rate of mass loading in the torus leading in turn to faster radial transport and the need for greater field-aligned currents to couple to the ionosphere. We expect these field-aligned currents to be time varying, just as they are further out in the magnetosphere [*Russell et al*., 2001c]. They are candidates for both energizing and diffusing the energetic particles radially. If the events are small and short-lived they could produce a localized enhancement near Io that drifts slowly in longitude. If the event is larger it could produce a disturbance over a wide longitude and extended radial range. We note that the energetic events seen at lower energies [*Mauk et al*., 1999] may also be produced in this manner. The one injection identified in time and space by *Mauk et al*. [1999] was located at a point radially aligned with Io.

We note that these enhanced particle fluxes do decay rapidly. The enhanced fluxes of C22 had died away by the time Galileo returned to the inner magnetosphere one month later on C23. The low J0 flux levels suggest that the flux levels of C23-E26 do not represent the ground state of the magnetosphere but that energization events are occurring throughout the period. Nevertheless these events are significantly smaller than the C22 event. Thus it appears that Io frequently produces small energization events and on rare occasions produces large events such as that on C22.

CONCLUSIONS

The star sensor is an uncalibrated energetic particle sensor. Nevertheless we can learn something about the behavior of the inner radiation belts from it. The presence of asymmetries inbound and out suggests that the responsible particles may be electrons with energies of the order of 3-30 MeV. Generally the count rates are greatest at the equator as expected for trapped energetic particle fluxes. Near the orbit of Io there is a dip near the equator, as expected from interaction with the torus [*Lagg et al*., 1998]. Smaller events near the Io orbit occur moderately frequently so that about 50% of the passes show evidence of some recent event. On one of our 6 passes, C22, evidence for a large event affecting all longitudes and radial distances out to 8 R_J was seen. On another of our passes J0, the inner magnetosphere apparently had been quiet for quite some time and the fluxes decayed to rather low levels. In short the radiation belt outside of the Io orbit is a highly variable region even though the region inside Io appears to be much more stable.

ACKNOWLEDGMENTS

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