Origins of the slow and the ubiquitous fast solar wind

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Abstract

We present in this Letter the first coordinated radio occultation measurements and ultraviolet observations of the inner corona below 5.5 R_s, obtained during the Galileo solar conjunction in January 1997, to establish the origin of the slow solar wind. Limits on the flow speed are derived from the Doppler dimming of the resonantly scattered component of the oxygen 1032 and 1037 Å lines as measured with the UltraViolet Coronagraph (UVCS) on the Solar and Heliospheric Observatory (SOHO). White light images of the corona from the Large Angle Spectroscopic Coronagraph (LASCO) on SOHO taken simultaneously are used to place the Doppler radio scintillation and ultraviolet measurements in the context of coronal structures. These combined observations provide the first direct confirmation of the view recently proposed by Woo and Martin (1997) that the slow solar wind is associated with the stalks of streamers. Furthermore, the ultraviolet observations also show how the fast solar wind is ubiquitous in the inner corona, and that a velocity shear between fast and slow solar wind is localized along the radial extensions of the boundaries of streamers.

Subject heading: Sun - Corona, Sun - Solar wind

1. Introduction

The solar wind is a direct manifestation of the coronal heating processes which continue to elude us. For over three decades, observations in interplanetary space have identified two types of wind: a slow component with highly variable physical properties also characterized by speeds typically below 500 km/s, and a much less variable fast wind flowing on average at 750 km/s (e.g., Schwenn 1990, Gosling et al 1995). Connecting these two types of winds to their origins at the Sun is still not resolved. The prevailing view is that the fast solar wind originates from polar coronal holes, and occasionally from coronal holes at low latitudes (see for example, Krieger, Timothy, & Roelof 1973, Hundhausen 1977). In the absence of equatorial coronal holes, observations of fast wind at low latitudes have been attributed to the faster than radial expansion of the magnetic field lines defining the interface between polar coronal holes and streamers since the boundaries of polar coronal holes, as defined on the solar disk, do not extend below 50° latitude even at solar minimum (see for example Harvey 1996). The source of the slow solar wind, on the other hand, generally believed to be associated with the highly structured and variable streamer belt (Gosling 1997), has remained more enigmatic.

Important clues regarding the association of fast and slow solar wind with the corresponding magnetic field structures in the corona have recently emerged from the interpretation of remote sensing radio occultation measurements. Large-scale gradients in velocity indicated that the slow wind emanated from localized sources in the corona overlying the streamer belt (Woo 1995). That the slowest wind coincided with conspicuously high levels of density fluctuation characteristic of coronal streamer stalks (Woo et al. 1995) provided the first observational evidence that the axes (or stalks) of streamers were the sources of the slow solar wind (Woo & Martin 1997). By comparing ranging measurements of path-integrated density with simultaneous white light observations, Woo and Habbal (1997a) found that structures in the low corona extended radially outwards into interplanetary space. The radio observations thus strongly suggested that the corona was dominated by radially expanding raylike structures originating from polar coronal holes as well as the quiet Sun. Furthermore, low levels of density fluctuation characteristic of the fast wind (Woo 1995, Woo & Gazis 1993, Woo & Habbal 1997b) were also found to originate from coronal holes and quiet Sun regions. These results, taken together with the predominance of the fast solar wind found by Ulysses during its polar passages, led Woo and Habbal (1997a) to conclude that the fast solar wind must originate not only from polar coronal holes but also from the quiet Sun, and that it propagates along raylike structures originating from both regions.

The advent of the Galileo solar conjunction in January 1997 and the capabilities of the UVCS (Kohl et al. 1997) offered the first opportunity to test the recent interpretations of the radio measurements. We present in this Letter the first such coordinated measurements. We show how these simultaneous observations provide the first direct confirmation that the slow solar wind is limited to the stalks of streamers, while the fast wind fills the rest of the heliosphere.

2. UVCS Observations

UVCS on SOHO (Kohl et al. 1995) has proven to be a powerful tool for probing the physical conditions in the inner corona (Kohl et al. 1997, Noci et al. 1997). One of the unique advantages of this instrument is the measurement of coronal spectral lines formed primarily by the resonance scattering of ions in the corona of the corresponding lines emitted from the solar disk. These measurements extend to at least 3.5 R_s in coronal holes, and to 10 R_s in denser coronal plasmas (Kohl et al. 1995, 1997).

The strongest of these lines are the Lyα 1216 Å and the O VI 1032 and 1037.6 Å lines. One of the interesting properties of the oxygen lines (and other minor ion lines observed by this instrument) is that collisional excitation also contributes to the formation of the line. However, as the ions start to flow outwards in the corona, the fraction of the spectral line formed by resonance scattering becomes Doppler-shifted out of resonance with the disk emission (Kohl & Withbroe 1982, Noci, Kohl, & Withbroe 1987, Withbroe et al. 1982). Subsequently, the relative ratio between these two lines changes drastically. Known as Doppler-dimming, this effect influences the two lines differently because of the additional pumping of the 1037.6 Å line by the disk emission of the C II line at 1037 Å . The Doppler dimming and pumping effect has been demonstrated successfully with UVCS in a number of coronal hole observations (Kohl et al. 1997).

A ratio of 2 occurs for a flow speed of 94 km/s. A minimum in the ratio occurs for a flow speed of 188 km/s when the C II line in turn becomes Doppler-shifted out of resonance (Noci et al. 1987). Hence the ratio of the intensity of the two oxygen lines yields a direct measure of the outflow velocity of these ions. Although the ion flow speeds could be different from the proton/electron velocity, they are still valid proxies for fast versus slow wind. Indeed multifluid solar wind model computations show that the flow speed of minor ions, protons and electrons are very close in values in the inner corona (Li et al. 1997).

Taking advantage of the diagnostic tool offered by the ratio of the oxygen lines, as well as the contrasting signatures of the fast and slow solar wind in Doppler scintillation measurements, coordinated radio occultation and UVCS observations were carried out for the first time during the Galileo solar conjunction between January 17 and 20, 1997.

Figure 1 shows an image of the corona taken with the white light coronagraph (LASCO)(Brueckner et al. 1995) on SOHO on January 17 during this observing period. The slit positions of the UVCS detector were chosen to coincide with the passage of the radio signal from Galileo through the corona starting on January 17. The south polar coronal hole measurements on January 19 were made by UVCS alone when Galileo was occulted by the Sun. The measurements off the west limb on January 20 followed Galileo on the egress.

To further map the solar wind velocity around a streamer, a second set of UVCS measurements were taken on April 23, 25, and 27, 1997. These were centered on the axis of a well-isolated streamer on the west limb at position angle PA = 267° (measured counterclockwise from heliographic north), as well as at 20° and 40° north of that position (see Figure 2).

By measuring the intensity of the two oxygen lines and their ratio along the slits for different heliocentric distances, contours of the intensity ratio equal 2 (or equivalently an ion flow speed of 94 km/s) for the two observation sets were obtained. These are shown as white lines in Figures 1 and 2. UVCS observations away from the axes of the streamers in both data sets offered the first direct evidence for the sharp transition in flow speed from the axis of the streamer to the ambient corona at any given heliocentric distance. A typical example illustrating this transition is shown in Figure 3 for the UVCS observations of April 27 at 3.5 R_s at 20° north of the streamer axis (see Figure 2). This figure clearly illustrates how the relative change in peak intensity and shape of the two oxygen line profiles varies significantly as a function of latitude, or more relevantly, as a function of position angle away from the streamer axis or stalk. Also worth noting is the contour on the west limb on January 20. The ratio is of the order of 2 across the two streamer stalks. The ratio drops very quickly south of this contour, an indication of a very sharp gradient in that region.

Plots of the ratio of the two oxygen lines versus heliocentric distance for different position angles S.4 = 0°, ± 10° and ± 20° measured north (+) or south (-) with respect to the axis of the streamers are shown in Figure 4. The top three panels correspond to the January east limb observations, and the lower four panels to the April observations. For small heliocentric distances the data were binned over 2-4'. At distances larger than 3.5 R_s the data were binned over 11' (corresponding to an uncertainty of 2°) when the streamer axis was not in the field of view. It is clear from these plots that the wind reaches a speed of 94 km/s (or ratio = 2) around 4.5 R_s along the axes of streamers

(SA = 0°). In contrast, the wind is faster closer to the Sun as it moves away from the axis of the streamers, for example, at 3.5-4 R_s for SA = ± 10” , or 2.5-3 R_s for SA = ± 20°. The first minima seen at ±20° are very close in heliocentric distances to those found in coronal holes, and correspond to 188 km/s. An uncertainty of 0.5 in the ratio corresponds to an uncertainty of 25 km/s in speed.

Most striking in the ratio=2 contours is the sharp latitudinal gradient in wind speed that occurs close to the axis of the streamers. However, not only is the change in ratio indicative of changes in solar wind character, but so is the width of the spectral lines. As shown in Figure 3, the lower ratio and broader profile are typical of a fast and hot wind (as far as the oxygen ions are concerned). These are comparable to UVCS measurements in polar coronal holes described by Kohl et al. (1997). This combination is also a strong indication of the anisotropy of the velocity distribution in the fast wind as shown in Kohl et al. (1997). Since the line ratios are derived from measurements along the line of sight, the flow speed is high over a large fraction of the line of sight. Along the axis of the streamer, on the other hand, the ratio is higher, and the lines narrower, as reported in earlier UVCS observations of streamers (Noci et al. 1997), an indication of cooler and slower flowing ions.

3. Radio Occultation Measurements

The corresponding Doppler scintillation measurements made by Galileo in January are shown in Figure 5. These measurements are characterized by relatively low levels of Doppler scintillation except on January 22. The white-light image of January 22 in Figure 6 shows that the enhanced Doppler scintillation on January 22 is caused by a streamer stalk intercepting the Galileo radio path. Results from these coordinated measurements, therefore, reinforce those obtained from comparing Doppler scintillation and solar wind speed measurements (Woo & Martin 1997), i.e., low levels of Doppler scintillation observed away from streamer stalks are a proxy for the fast wind, while pronounced enhancements in Doppler scintillation are a proxy for coronal streamer stalks in the absence of coronal mass ejections (Woo 1997).

4. Discussion and Conclusion

Radio occultation measurements provided the first hints of the *source* regions of the fast and slow solar wind and the impetus for the present coordinated observations. The results reported here illustrate the power of the UVCS instrument to provide more definitive answers, since it can map the whole plane of the sky.

Although a number of UVCS observations of streamers have been made since the launch of SOHO (see, e.g., Noci et al. 1997), the coordinated radio scintillation and ultraviolet observations of the inner corona presented here are the first of their kind. The most straightforward result to emerge from these coordinated observations is that low levels of radio scintillation are indeed associated with fast solar wind, while the pronounced peaks result from the passage of the radio signal through the stalks of streamers. More importantly however, this work provides the first confirmation of the perspective recently developed from radio occultation measurements (Woo 1995, Woo & Habbal 1997a, Woo & Martin 1997), namely that the stalks of the streamers are the locus of the slowest solar wind, while the fast solar wind dominates the corona.

These coordinated observations also confirm the existence of sharp wind speed gradients found earlier by radio occultation measurements of the corona (Woo 1995). As shown in Figures 1 and 2, around 2 R_s, the 94 km/s contours cross the raylike structures prevailing in the corona from the poles down to the streamer stalks. As the streamer stalk forms, a sharp gradient in the transition from fast to slow wind also emerges and converges towards the stalk. Undoubtedly, remnants of this velocity shear survives in interplanetary space since it has been frequently observed in insitu observations beyond 0.3 AU (e.g. Schwenn et al. 1978, Rhodes and Smith 1981). The sharp gradients observed in interplanetary measurements have been often associated with the crossings of the radial boundaries of equatorial coronal holes as the Sun rotated across the field of view of the plasma instruments (e. g., Schwenn et al. 1978). However, no sharp latitudinal gradients associated with the radial boundaries of polar coronal holes were measured by Ulysses out of the ecliptic and at high latitudes (Phillips et al. 1995). The UVCS results clearly show that the velocity shears are associated with the streamer stalks.

In fact, there is no clear distinction in the white light images in morphology between the extension to large heliocentric distances of the rays originating from polar or low latitude regions (see Figure 6). These observations thus also confirm the view recently proposed by Woo and Habbal (1997a) that the fast solar wind does not originate primarily from polar coronal holes, but that its ubiquitous nature, so vividly evident in the Ulysses measurements, derives from its origin in the quiet Sun too. This new view also provides a natural explanation for the absence of significant latitudinal gradient in the magnetic field observed by Ulysses at high latitudes (Balogh et al. 1995).

That there exist two types of solar wind with different physical characteristics can be readily understood if we consider their corresponding magnetic sources. It seems plausible that the radially extending raylike structures originate within the boundaries of supergranular cells which indiscriminately cover the solar surface. These cells are preserved in coronal holes because of the absence of large scale closed magnetic field lines. In the quiet Sun, the supergranular cells at coronal heights are essentially preserved except for occasional disruptions by large scale magnetic field lines interconnecting widely separated magnetic regions. Indeed, close inspection of eclipse observations of the Sun clearly show the coexistence of open and closed magnetic structures in the plane of the sky (e.g. Koutchmy 1977, November & Koutchmy 1996).

The axes of the streamers, which carry the slow solar wind, on the other hand, belong to the large scale coronal structures that have dominated our impression of the corona for so long and which derive from deep-rooted multipolar fields.

The new clues provided by the results of this study should lead to new perspectives in the search for the elusive coronal heating mechanisms of the solar wind.

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Figure Captions

Figure 1. White Light images of the corona taken with the LASCO C2 coronagraph on SOHO on 17 January. The bright object in the east below the equator is Jupiter and indicates the approximate location of Galileo. The field of view spans 2 to 6 R_s. The spatial length of the field of view defined by the slit of the UVCS detector is approximately 2 R_s. Shown as black vertical lines are the slit positions, located at 1.9, 2.5, 3, 4, 4.7 and 5.5 R_s on the east limb, at 1.9 R_s in the south polar coronal hole, and at 4, 4.7 and 5.5 R_s at the west limb. They are perpendicular to the radial direction at position angles PA = 97°, 180° and 247° respectively, measured counterclockwise from heliographic north. The white contours mark the ratio of the oxygen 1032/1037 line intensities equal to 2, or, equivalently 94 km/s.

Figure 2. Same as Figure 1 for observations on 23, 25 and 27 April, 1997. The background white light corona from LASCO was taken on 27 April. These observations were made with slit positions perpendicular to the axis of the streamer at PA = 267° at 2.3, 3., 3.5, 4., 4.5, and 5 R_s. Additional observations were made at 20° north of these positions and one at 400 north of the position at 3 R_s. Here too the white contours mark the ratio of the oxygen 1032/1037 line intensities equal to 2.

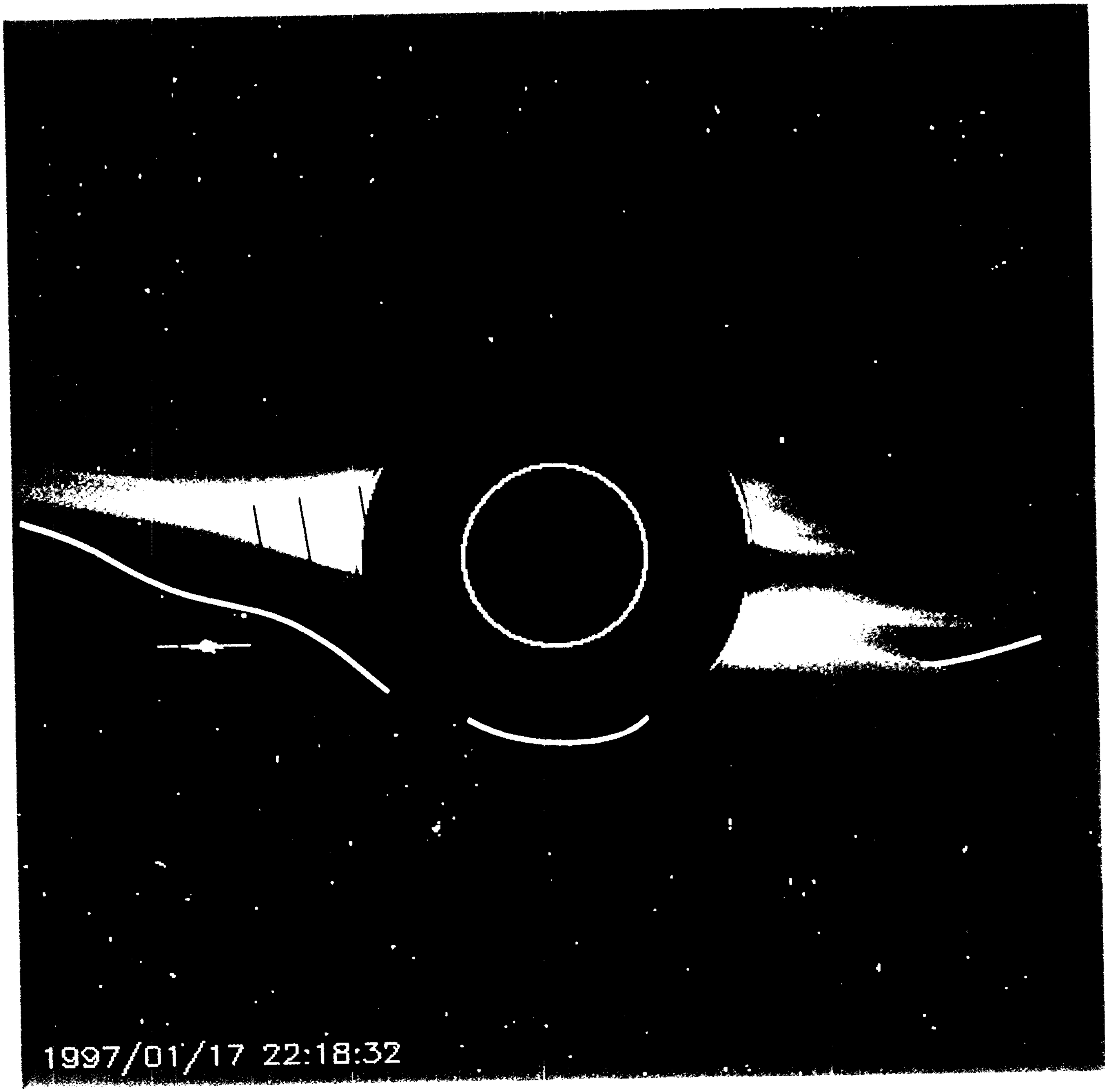
Figure *3.* Top: False-color image of the intensity of the O VI 1032, 1037.6 Å and Ly β lines along the slit at 3.5 R_s, 20° north of the streamer axis of Figure 2. The horizontal axis is the spectral direction, and the vertical axis represents the spatial direction. The spectral resolution is 0.28 Å per bin. Because of the roll angle of UVCS, north faces down. Bottom: (a), (b) and (c) are the profiles of the two oxygen lines integrated over 4.5’, 5.25’ and 11.5’ fields of view, respectively, as indicated by the space between the arrows in the image above. The ratio of the line intensities is (a) 2.1 ± 0.1, (b) 1.7 ± 0.25 and (c) 1.4 ± 0.5 respectively.

Figure *4.* Plots of the ratio of the two oxygen lines versus heliocentric distance R/R_s

for different position angles SA = 0°, ± 10° and ± 20° measured north (+) or south (-) with respect to the axis of the streamers. The top three panels correspond to the January east limb observations, and the lower four panels to the April observations.

Figure 5. Radio Doppler scintillation measurements by Galileo during its solar conjunction in January 1997.

Figure 6. White light image from the LASCO C3 coronagaph, with a field of view extending from 3.7 to 30 R_s, on 22 January 1997. Jupiter (the bright object) indicates the point of closest approach of the line of sight radio path from Galileo.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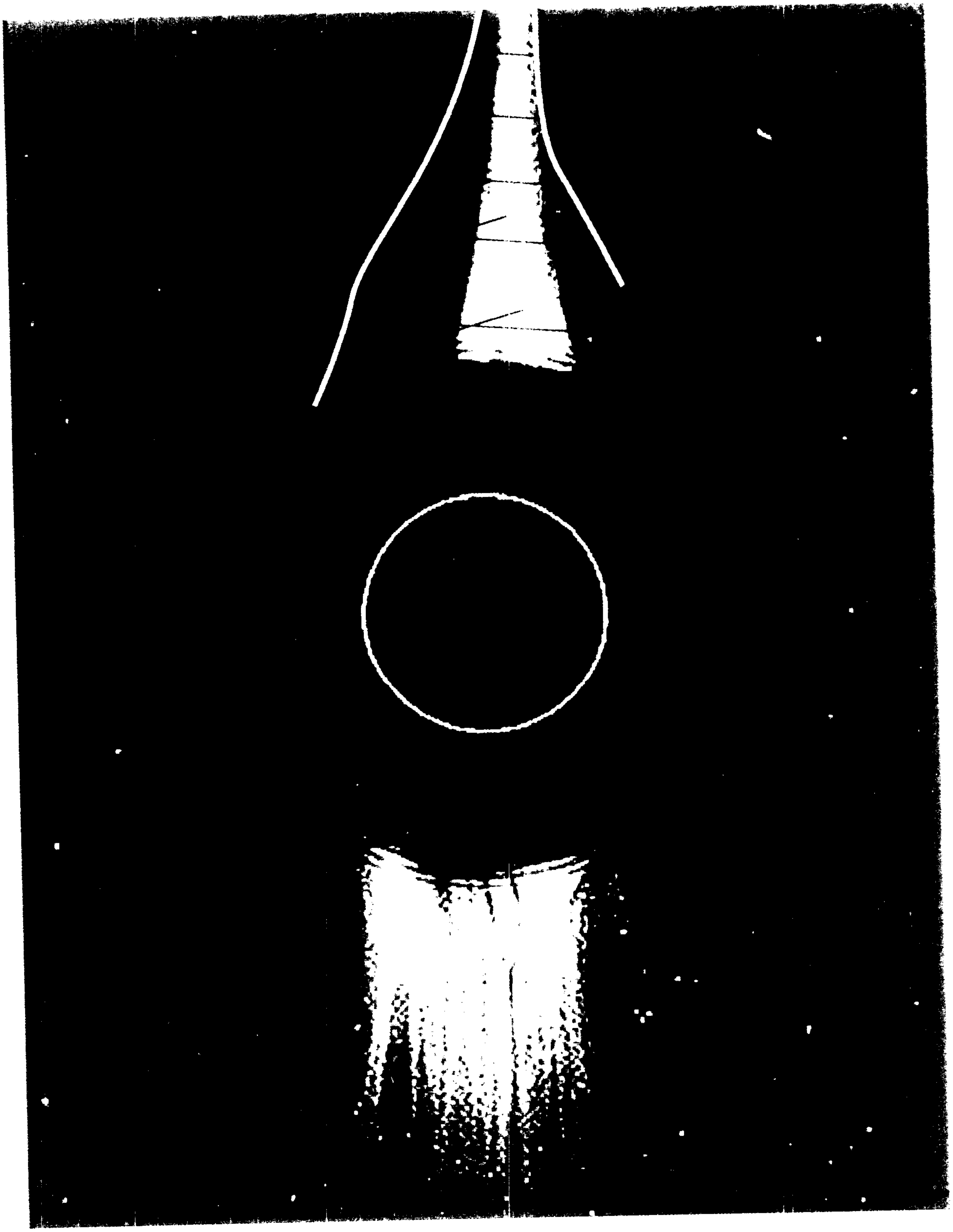

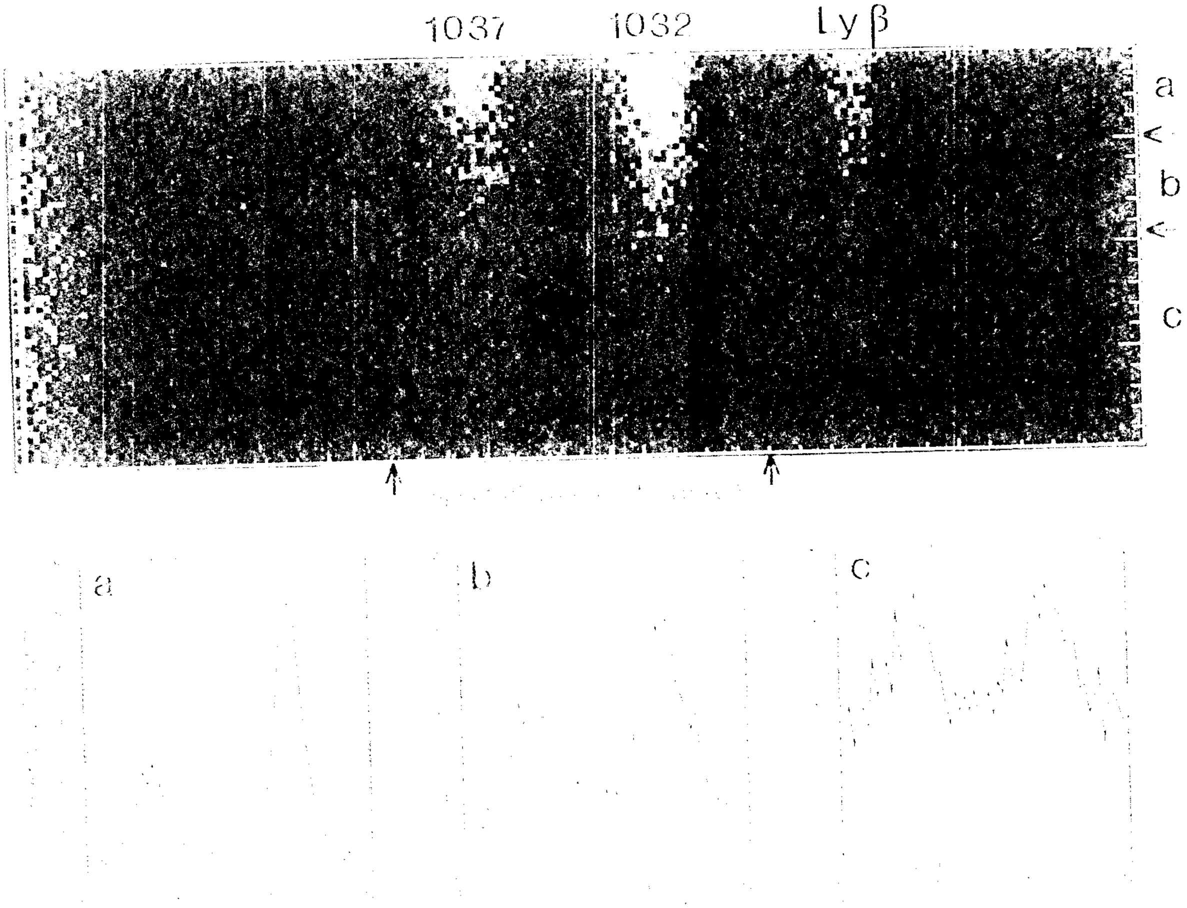
1037
1032
Ly β
a
b
c
a
b
c

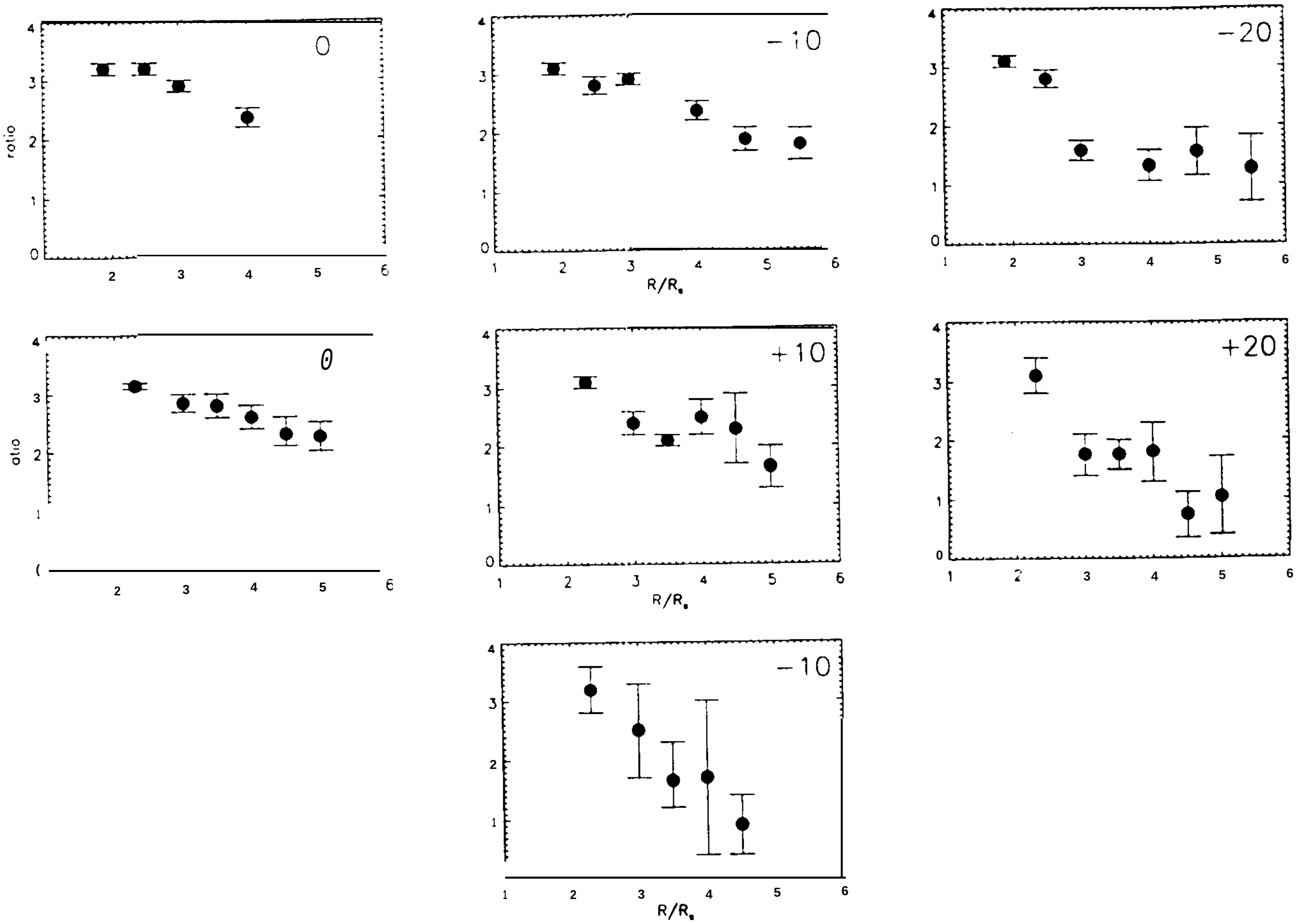

FIG. 4

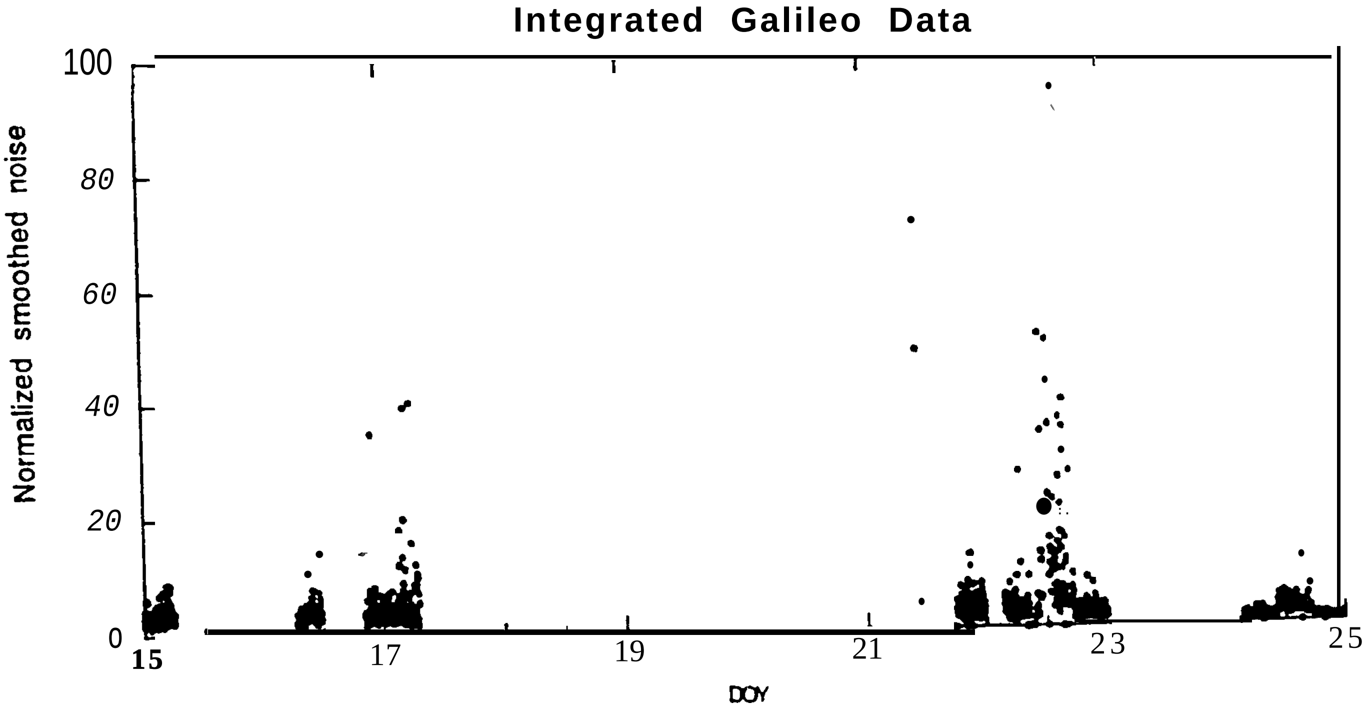
Integrated Galileo Data
Normalized smoothed noise
100
80
60
40
20
0
15
17
19
21
23
25
DOY

FIG. 5