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High-latitude Ulysses observations of the H/He intensity ratio under solar minimum and solar maximum conditions

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Abstract. We analyze measurements of the 0.5-1.0 MeV/nucleon H/He intensity ratio from the Ulysses spacecraft during its first (1992-94) and second (1999-2000) ascent to southern high latitude regions of the heliosphere. These cover a broad range of heliocentric distances (from 5.2 to 2.0 AU) and out-of-ecliptic latitudes (from 18 °S to 80°S). During Ulysses' first southern pass, the HI-SCALE instrument measured a series of enhanced particle fluxes associated with the passage of a recurrent corotating interaction region (CIR). Low values ($\sim$6) of the H/He ratio were observed in these recurrent corotating events, with a clear minimum following the passage of the corotating reverse shock. When Ulysses reached high southern latitudes ($>$40 °S), the H/He ratio always remained below $\sim$10 except during two transient solar events that brought the ratio to high ($>$20) values. Ulysses' second southern pass was characterized by a higher average value of the H/He ratio. No recurrent pattern was observed in the energetic ion intensity which was dominated by the occurrence of transient events of solar origin. Numerous CIRs, many of which were bounded by forward and reverse shock pairs, were still observed in the solar wind and magnetic field data. The arrival of those CIRs at Ulysses did not always result in a decrease of the H/He ratio; on the contrary, many CIRs showed a higher H/He ratio than some transient events. Within a CIR, however, the H/He ratio usually increased around the forward shock and decreased towards the reverse shock. Throughout the second ascent to southern heliolatitudes, the H/He ratio seldom decreased below $\sim$10 even at high latitudes ($>$40°S). We interpret these higher values of the H/He ratio in terms of the increasing level of solar activity together with the poor definition and short life that corotating solar wind structures have under solar maximum conditions. The global filling of the heliosphere by transient solar events and the fact that in 1999-2000 Ulysses observed only intermediate ($<$650 km s^{-1}) solar wind speed (whose contents in pick-up He is less energetic than in the fast solar wind streams observed in 1992-1994) favored the protons with respect to alpha particles. Hence the fact that the average values of the H/He ratio observed by Ulysses during the rising phase of the solar cycle (1999-2000) were higher than those observed during the declining phase (1992-1994).

INTRODUCTION

The study of the suprathermal proton-to-helium abundance ratios during different phases of the solar cycle can be used as indicator of how interplanetary acceleration mechanisms and "seed" particle populations change over the solar cycle. Previous studies [1, 2] have shown a fundamental solar cycle variation in the particle flux abundances. Shields et al. [1] showed that at the heliocentric distance of 1 AU solar minimum fluxes tend to be richer in helium than the fluxes measured during active periods. Richardson et al. [2] noted that the element abundances of corotating events (also observed at 1 AU) showed a clear transition from solar maximum to solar minimum. Solar minimum corotating events have element abundances that are well differentiated from the abundances measured during solar energetic particle (SEP) events, while at solar maximum the abundances in corotating events are more SEP-like [2].

Corotating energetic particle events are associated with the compression regions formed by the interaction between slow and fast solar wind streams. The rather simple configuration of the solar corona found at solar minimum, with large coronal holes over the polar caps, restricts the range of interaction between fast and slow solar wind to low heliographic latitudes ($\lesssim$40°). The stability of the solar corona during solar minimum leads to the recurrent observation of compression regions on each solar rotation, and hence the name of corotating interaction regions (CIRs). During solar maximum, the more complex arrangement of the solar corona, with small-scale coronal holes observed at all latitudes, increases the angular range where the interaction between slow and fast solar wind may take place. The dynamic character of the solar corona during active periods together with the small scale of the coronal holes leads to a less evolved and less periodic character of the CIR structures [3].

The out-of-ecliptic orbit of the Ulysses spacecraft with a period of 6.2 years allows us to study these solar cycle variations over a broad range of heliographic latitudes. At the end of 1992, the Ulysses spacecraft was at a distance of 5.2 AU from the Sun and moving south beyond 18°S. The spacecraft reached its most southern heliographic latitude of 80.2°S at a radial distance of 2.3 AU from the Sun in mid-September 1994. After a complete orbit over the poles of the Sun, in January 1999 Ulysses was again at a distance of 5.2 AU from the Sun and moving south beyond 18°S. During its second out-of-ecliptic orbit around the Sun, it reached a maximum latitude of 80.1°S at the end of November 2000. While the first excursion to southern latitudes (1992-1994) occurred during the declining phase of the solar cycle 22, the second ascent to high latitudes (1999-2000) coincided with the rising phase of the 23rd solar cycle.

In this paper we report measurements of the 0.5-1.0 MeV/nucleon H/He ratio for the first and second Ulysses' southern passes. While previous studies of the proton-to-helium ratio have limited their analysis to the ecliptic plane and at 1 AU from the Sun [1, 2, 4], or in the outer heliosphere but under solar minimum conditions [5, 6, 7, 8], we extend these studies to high heliographic latitudes and for solar maximum conditions. We describe how the observed H/He ratio is affected by the occurrence of transient events and the arrival of coronal mass ejections (CMEs) and CIRs. We compare the evolution of the H/He ratio at high heliolatitudes during solar maximum and solar minimum and interpet its evolution in terms of the possible sources of energetic particles.

OBSERVATIONS

The measurements presented here were made with the CA (Composition Aperture) telescope of the HI-SCALE (Heliosphere Instrument for Spectra, Composition and Anisotropy at Low Energies) on the Ulysses spacecraft [9]. The CA telescope consists of a three element Si solid state detector telescope with a 5μ-thick first detector followed by two 200μ-thick second and third detectors. It uses a $\Delta E \times E$ detection scheme to measure particles of kinetic energy E satisfying the coincidence requirement in the first two detectors without triggering the third (anticoincidence) detector. The detected particles are analyzed using a four level priority-controlled pulse height analyzer (PHA). This analysis provides an unambiguous determination of the energetic proton and helium nuclei, however it does not resolve the charge state of the particles. The small (but finite) backgrounds from the H and He PHA rates have not been subtracted; therefore, the H/He ratio is only computed when none of the rates is near background. We also use measurements from the Ulysses solar wind plasma experiment [10] and magnetometer [11], in order to identify the arrival of CMEs and CIRs at the spacecraft. The occurrence of counterstreaming electron events have been used to determine the passage of CMEs over the spacecraft [12] and also those time intervals when Ulysses remains connected to CIR shocks [13].

Figure 1 shows the spin-averaged, three-day averaged fluxes of 0.5 to 1 MeV/nucl protons and helium together with the H/He ratio and the solar wind speed from 24 October 1992 to 24 October 1994 (top panel) and from 1 January 1999 to 1 January 2001 (bottom panel). During those two periods, Ulysses covered the heliocentric distances from 5.20 AU to 2.02 AU, and heliolatitudes from 19°S to 75°S, reaching a maximum latitude of 80.2 degrees in mid-September 1994 for the first orbit and at the end of November 2000 for the second orbit.

Solar Minimum: First Southern Pass

A recurrent pattern of particle flux increases with ~26-day periodicity was observed during the first southern pass. These enhancements were closely associated with the encounter of a recurrent high-speed (>800 km s^{-1}) solar wind stream. A compression interaction region, mostly bounded by forward/reverse shock (FS-RS) pairs, was formed at the leading edge of these high-speed streams (indicated by gray rectangles in the upper part of panel D in Figure 1). Rotation 15 at a latitude of ~34°S was the last rotation where a corotating FS-RS pair was observed. From then on, the spacecraft was immersed in the flow from the polar coronal hole and only reverse shocks were regularly observed. Above ~42°S, however, CIR-reverse shocks were observed only sporadically [14]. Before the disappearance of recurrent CIR shocks, peaks in the ion intensity were observed close to both the forward and the reverse shocks. Even after no corotating shocks were seen (poleward of ~42°S), the recurrent peaks in the particle intensities were still observed, although the intensity decreased with increasing latitude. Superimposed on this regular feature were several CME-related particle events (as in rotations 6, 14, 23, 24 and 26 indicated by black rectangles in the bottom part of the panel D in Figure 1), as well as particles associated with transient events of solar origin (as in rotations 6, 15, 23 and 24). Between rotations 7-8, 10-11, 11-12, 15-16, 16-17, and 18-19, Roelof et al. [15] noticed the occurrence of “inter-events” (indicated by black dots in panel B of Figure 1). Some of the characteristics of all these particle increases have been presented elsewhere [e.g., 5, 15] and the reader is referred to these papers for the salient details of these events.

Simnett et al. [16] performed a detailed study of the the evolution of the H/He ratio rotation by rotation. The main results of their analysis, apparent in the top panel of Figure 1, are that (1) the H/He ratio shows low ($\lesssim$10) values at the corotating events (indicated by shaded areas in panels B and C of the Figure 1), and high ($\gtrsim$50) values at the events of solar origin; (2) the H/He ratio decreases within the CIR, reaching a minimum value at the time of the reverse shock or during the crossing of the high-speed solar wind stream; (3) as Ulysses becomes immersed in the high-speed polar solar wind, the H/He ratio always remains below $\sim$10, with the exception of the two transient events in rotations 23 and 24. We note that the occurrence of an event of solar origin (as in rotations 23 and 24, or between rotations 10-11 and 11-12) may produce an increase of the H/He ratio which remains high for the subsequent solar rotations. We refer to [16] for further details on the evolution of the H/He ratio during the first southern pass.

Solar Maximum: Second Southern Pass

The second southern pass showed a completely different pattern. Ulysses observed both slow ($\sim$350 km s^{-1}) and an irregularly structured intermediate-speed ($\lesssim$650 km s^{-1}) solar wind [3]. The highest solar wind speed for the whole second southern pass ($\sim$750 km s^{-1}) was observed on day 193 of 2000 when Ulysses was at 62°S. Very low-speed ($\sim$300 km s^{-1}) solar wind was observed even when Ulysses was over the south pole. Although the speed difference between the slow and intermediate-speed solar wind was small, numerous stream interactions were well developed, many of which were bounded by FS-RS pairs [3]. While several of these interaction regions reappeared at roughly the solar rotation period over a few consecutive rotations (see for example the time interval shown in Figure 2), these structures were much less periodic than those observed in 1992-1993. A higher number of CME disturbances were also observed in the solar wind, with a larger rate at lower heliolatitudes, but still present at high latitudes [3].

In contrast to the first southern pass, energetic ion intensities fluctuated without any consistent pattern. Whereas at solar minimum the lowest ion fluxes occurred between two consecutive corotating events (unless there was an inter-event of solar origin), proton and helium fluxes at solar maximum were elevated throughout the second orbit. There was only one period between days 230 and 256 of 2000 when the proton fluxes were just one order of magnitude above background levels and helium fluxes were close to background levels (in that period we do not compute the H/He ratio). While solar minimum particle intensities were low or at background level at high heliolatitudes ($\gtrsim$70°S), at solar maximum several transient events were still observed even at 80°S. The elevated fluxes observed throughout the second southern pass indicate that the heliosphere was essentially completely populated at all heliolatitudes and heliolongitudes; the inner heliosphere was acting as a “reservoir” of low-energy ions [17]. The complicated temporal structures of the energetic particle intensities during the second southern pass make the classification of the fluxes in corotating or transient events difficult.

The H/He ratio showed high ($\gtrsim$ 20) values throughout the second southern pass, with only occasional decreases below $\sim$10. There was no latitude dependence of the H/He ratio which remained high even at high heliolatitudes. Low values of the H/He ratio do not seem to be always correlated with high-speed solar wind streams. In fact, examination of the H/He ratio on a expanded time scale shows that the arrival of an interaction region or of an intermediate-speed stream does not always produce a decrease of the H/He ratio. Figure 2 shows in detail the first 4 months of 1999 when a recurrence of six CIRs bounded by FS-RS pairs (gray shaded bars) was observed by Ulysses. The top panel of Figure 2 shows the small-scale southern coronal hole origin of the intermediate ($\sim$600 km s^{-1}) solar wind streams generating this sequence of CIRs. Ballistic projection of the solar wind and the negative magnetic field polarity observed during these streams support our identification. The arrival of CMEs after CIRs number 2 and 3 disturbed the structure of the solar wind streams observed at Ulysses. Numerous transient events (indicated by T’s in panel A) occurred during that time interval. Near-relativistic electron flux increases observed on the ACE and Ulysses spacecraft together with ground-based solar observations were used to identify these events as being of solar origin [18].

Throughout the first four months of 1999, the H/He ratio never decreased below 10 (with the exception of the interval between CIR 5 and 6). However, the arrival of the CIRs number 1, 4, 5 and 6 did produce a decrease of the H/He ratio, with a clear minimum towards the reverse shock or during the crossing of the fast stream. So at least qualitatively, the behavior of the H/He ratio in CIRs during early 1999 was similar to that in 1992-1994. Exceptions to this behavior are CIRs number 2 and 3. The onset of a transient event within the CIR number 3, produced an increase of the H/He ratio at the reverse shock. The decaying phase of a transient event superimposed on the CIR number 2 resulted in a high ($\sim$30) H/He ratio throughout the passage of this structure. The highest value of the H/He ratio is found at the forward shock of the CIR 4, with a value higher than the one observed during most of the transient events. The same happened for example during the CIR on day 120 of 2000 when Ulysses was at 53°S. This CIR showed the highest (>100) H/He ratio observed at high latitudes, and clearly contrasted with the subsequent transient event on day 126 of 2000 which decreased the H/He ratio to values around ∼20.

DISCUSSION AND CONCLUSIONS

The main results of the comparison between the 0.5-1.0 MeV/nucleon H/He ratio measured during the first Ulysses' southern pass and the second southern pass may be summarized as follows:

- particle fluxes at solar minimum are, on average, richer in helium than during solar maximum,
- whereas in solar minimum the H/He ratio allows us to distinguish between transient events and corotating events, during solar maximum such a distinction is not so clear,
- transient events of solar origin may be superimposed on CIR structures modifying the "normal" behavior of the H/He ratio, namely an increase around the forward shock and a decrease towards the reverse shock,
- the high-latitude heliosphere during solar maximum has characteristics similar to the heliosphere observed at the ecliptic plane. In particular, the H/He ratio does not show any latitudinal or radial dependence.

The different value of the H/He ratio observed for corotating events in solar maximum and solar minimum raises some questions about the seed particle population accelerated in CIRs. There are several heliospheric ion populations that are candidates for acceleration in CIRs, namely the thermal solar wind ions, a background population of solar energetic particles, and the interstellar and inner-source pick-up ions [19]. The low value of the H/He ratio, together with the overabundance of C and He relative to O observed in corotating events during solar minimum has been interpreted as a consequence of the pick-up He^{+} acceleration in CIRs [20, 5]. It is well-known that pick-up ions are favored over solar wind ions for injection into acceleration mechanisms, because of their higher energies in the solar wind frame [19]. However, since corotating streams are generally slower around solar maximum, and the maximum pick-up ion velocity scales directly with solar wind speed, their injection is less favored during solar maximum than in those cases when the solar wind is higher (i.e., during 1992-1994). Therefore, the lack of helium with respect to protons during the second southern pass is due to the following factors: (1) the larger number of transient events, richer in protons, leads to a global filling of the heliosphere over a large range of heliolatitudes, and (2) the reverse shocks formed by the interaction between slow solar wind and intermediate solar wind are weaker and less efficient in accelerating the lower energy pick-up helium existing in this intermediate-speed solar wind. A combination of these two factors fits in the new picture of particle sources sketched by Mason [19] where several particle populations contribute to an interplanetary reservoir [17] of suprathermal ions. This reservoir has time-dependent inputs; during solar minimum the particles accelerated by CIRs are dominant, whereas during activity maximum the transient events of solar origin increase their contribution.

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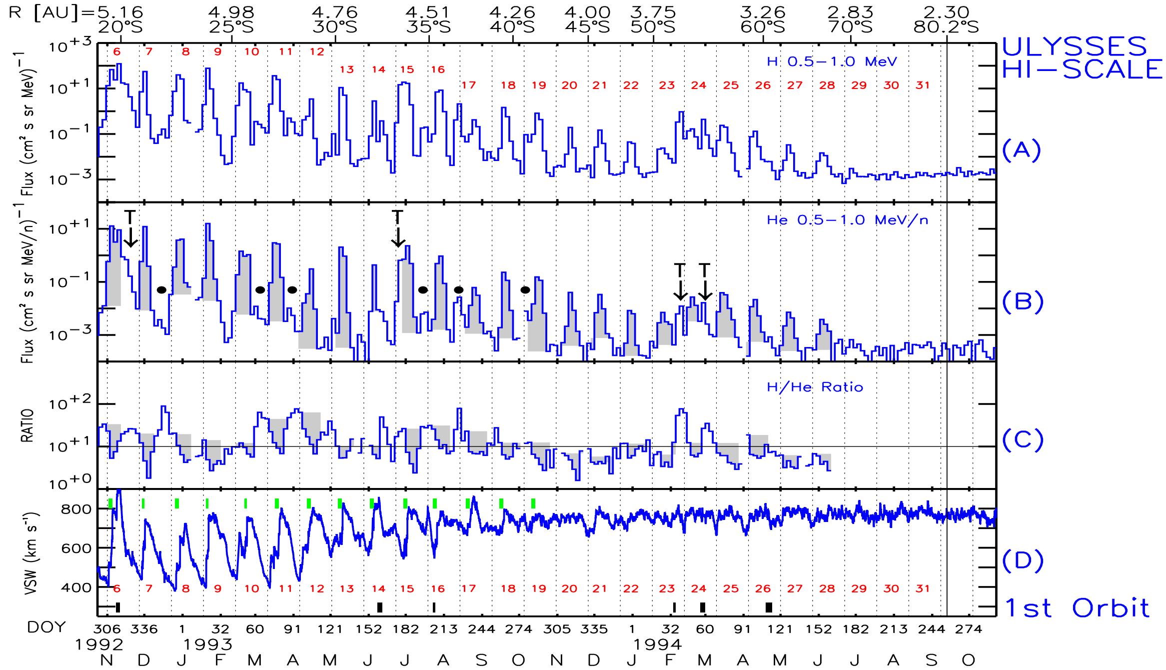

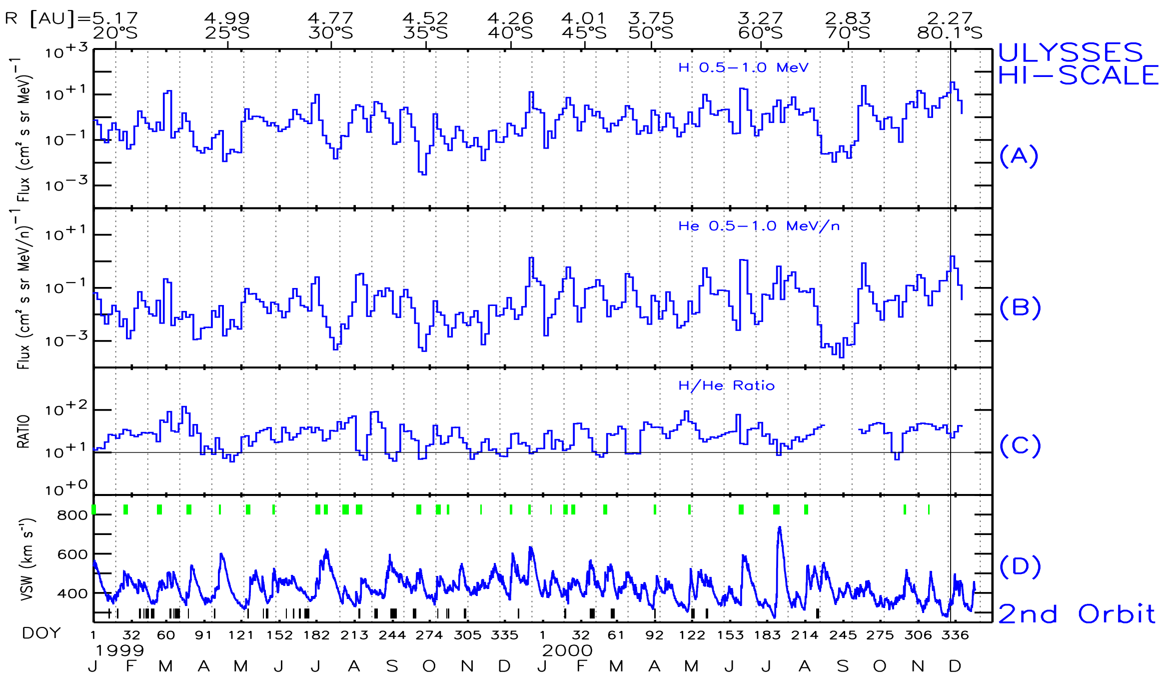

FIGURE 1. 3-day average of the (A) 0.5-1.0 MeV proton flux; (B) the 0.5-1.0 MeV/nucleon helium flux; and (C) the H/He ratio as measured by the HI-SCALE instrument [9]. (D) Houly averages of the solar wind speed as measured by the SWOOPS instrument [10]. The top panel extends from 24 October 1992 to 24 October 1994 and the bottom panel from 1 January 1999 to 1 January 2001. Shaded areas in the top panel identify the energetic particle events associated with CIRs. Upper rectangles in the solar wind panel (D) show the arrival of compression regions formed by the interaction between solar wind of different speeds; and black rectangles at the bottom of the solar wind panel (D) indicate the intervals associated with the passage of CMEs as identified by counterstreaming halo electron events in the solar wind [3]. The occurrence of transient particle events and “inter-events" are indicated by **T**’s and black dots in the top panel [15]. The vertical solid line marks the time when Ulysses reaches its maximum southern heliolatitude. Vertical dotted lines are spaced 26 days apart.

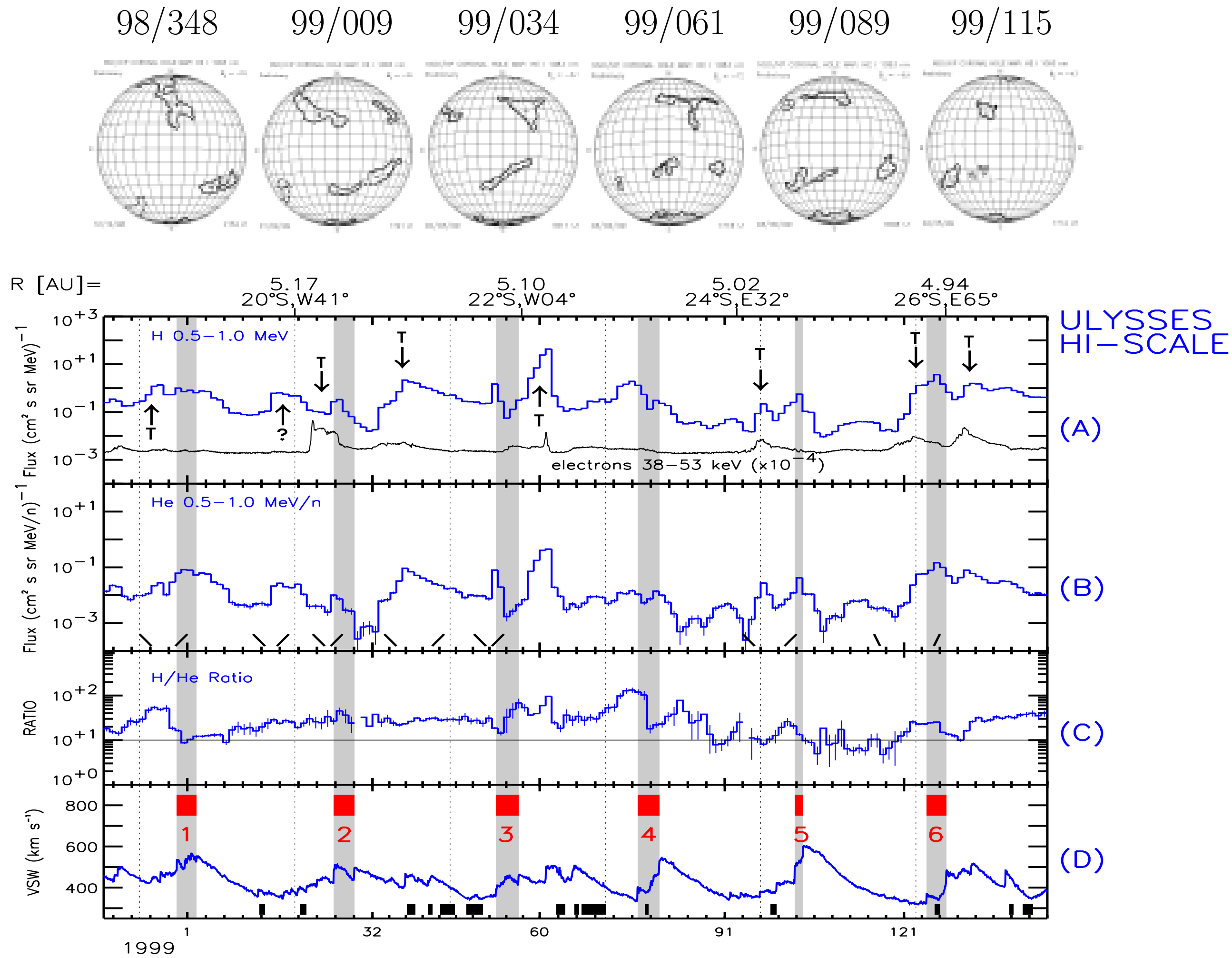

FIGURE 2. *Upper panel:* Coronal hole 1083 nm maps provided by the National Solar Observatory at Kitt Peak (solar Geophysical Data, 1999) taken on the day indicated at the top. The photospheric magnetic polarity of the southern hole is negative. *Bottom panel:* (A) Daily average of the 0.5-1.0 MeV proton flux and hourly average of the 38-53 keV electron flux; (B) daily average of the 0.5-1.0 MeV/nucleon helium flux; (C) daily average of the H/He ratio as measured by the HI-SCALE instrument [9]. (D) Hourly averages of the solar wind speed as measured by the SWOOPS instrument [10]. Time interval extends from 18 December 1998 to 21 June 1999. Gray shadow bars identify the passage of a recurrent CIR over Ulysses. Upper rectangles in the solar wind panel (D) show the arrival of compression regions formed by the interaction between solar wind of different speeds. Black rectangles at the bottom of the solar wind panel (D) indicate CMEs as identified by counterstreaming halo electron events in the solar wind [3]. Vertical dotted lines are spaced 26 days apart. Transient events are indicated by **T**. Slash and back-slash lines identify the change of magnetic field sector at Ulysses as measured from the magnetometer instrument [11] on Ulysses; from positive to negative polarity (/) and from negative to positive polarity (\). Note that the six recurrent CIRs appear with a $\sim$26 day periodicity and all show the same negative polarity.