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# OBSERVATION OF LITHIUM PICK-UP IONS IN THE 5- TO 20-KEV ENERGY RANGE FOLLOWING THE AMPTE SOLAR WIND RELEASES

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Abstract. Newly created 5- to 20-keV lithium ions were observed for limited time periods following the first Active Magnetospheric Particle Tracer Explorers (AMPTE) lithium release in the solar wind on September 11, 1984. The detection of these so-called "pick-up" ions by the time-of-flight spectrometer SULEICA (suprathermal energy ionic charge analyzer) on the AMPTE/IRM satellite depends critically on the orientation of the interplanetary magnetic field with respect to the directions of the solar wind and the spin axis of the IRM spacecraft, which was favorable only during the short time when these ions were seen. Our observations are compatible with a shell-like expansion of the Li cloud with velocities of about 2.5 km/s. The signatures by which the artificial pick-up ions are identified can also be used to detect and investigate natural pick-up ions.

## Introduction

Ions, freshly created from atoms in the solar wind (so-called pick-up ions), are immediately subjected to the Lorentz force due to the interplanetary electric field ($v_{sw}xB$) and the interplanetary magnetic field. As long as collective effects and pitch angle scattering can be neglected, one of the characteristics of pick-up ions is a cycloidal motion perpendicular to the local magnetic field. Sources of pick-up ions are planetary atmospheres, cometary comae and the interstellar neutral gas which penetrates into the heliosphere. In all of these three cases the ions are mainly created by solar UV radiation. The source, however, could also be a cloud of atoms injected artificially into the solar wind.

The purpose of this paper is to present the first observation of energetic lithium ions which originated from the lithium vapor releases from the Active Magnetospheric Particle Tracer Explorers (AMPTE)/IRM satellite. These $Li^+$ ions are detected in the solar wind with the time-of-flight spectrometer SULEICA (suprathermal energy ionic charge analyzer) on the AMPTE/IRM satellite in the energy range 5 to 20 keV.

The lithium releases started with the formation of a diamagnetic cavity around the IRM spacecraft for about 7 seconds as described by G. Haerendel et al. (unpublished manuscript, 1985) and Lühr et al. (this issue). After the cavity had vanished, the solar wind was still strongly disturbed for approximately 1 minute as could be seen from the wave activities (Häusler et al., this issue) and the electron heating (Paschmann et al., this issue). The ionization time constant of lithium has been estimated to be about one hour (Drapatz, 1977). Therefore Li ions are continuously created during the further expansion of the lithium vapor cloud at a rate sufficiently low so that the interplanetary field remains almost undisturbed. In order to gain energies up to 20 keV in the solar wind electric field the Li ions have to travel several thousand kilometers after being ionized. From the energy-time relationship we determine the evolution of the Li cloud and compare this with the results from the earlier phases of the release (Paschmann et al., this issue; Coates et al., this issue). Ions at the time of observations have already completed a consid-erable portion of their cycloidal path whose length is comparable to the distance of IRM from the bow shock. Therefore the possible influence of scattering processes on the particle trajectories on their way to the bow shock can be studied from the energy and angular distribution of the 5- to 20-keV lithium ions as measured by our instrument.

## Trajectories of Pick-up Ions

In a moving magnetized plasma, pick-up ions perform a cycloidal motion perpendicular to the magnetic field. By their signature, pick-up ions can be easily distinguished from solar wind ions which are highly collimated and streaming in the antisunward direction. For a given solar wind velocity and orientation of the interplanetary fields, pick-up ions show a unique relation between energy $E(\alpha)$, arrival direction $\varphi$, and distance S between the location of origin and that of detection, as can be seen in Figure 1. This holds as long as collective effects and scattering can be neglected. The maximum energy $E_{Max}$ of pick-up ions depends on the solar wind velocity $v_{sw}$, the ion mass $m_i$ and the angle $\vartheta$ between the interplanetary magnetic field and the solar wind:

$$E_{Max} = 4 \cdot \frac{m_i}{2} v_{sw}^2 \cdot \sin^2\vartheta \qquad (1)$$



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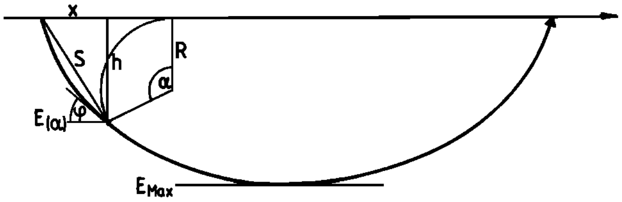


Fig. 1. Schematic drawing of the cycloidal trajectory of pick-up ions. $E_{Max}$ and $E(\alpha)$ are the maximum ion energy and the energy at a certain phase angle $\alpha$, respectively. $R_i$ is the ion gyroradius, S the distance between origin and registration of the ion, and h the distance of the ion from the projection of the solar wind flow line onto the plane of motion.

The actual energy $E(\alpha)$ is related to phase angle $\alpha$ of the cycloidal motion by

$$E(\alpha) = E_{Max} \frac{1-\cos\alpha}{2} \tag{2}$$

and the distance S can be written as

$$S = R_i \sqrt{(\alpha-\sin\alpha)^2+(1-\cos\alpha)^2} \tag{3}$$

In the case of a shell-like expanding lithium cloud the gyrophase as well as the energy of ions arriving at the center of the expansion depends on the radius S of the shell,

$$S = v_{exp} \; t \tag{4}$$

Here $v_{exp}$ is the expansion velocity and t the time after the release. Since the lithium was released symmetrically to the spacecraft (G. Haerendel et al., unpublished manuscript, 1985) and external forces (like radiation pressure from the sun and collisions with solar wind particles) can be neglected, the neutral vapor cloud moved with the satellite during the time of interest for the investigation.

Combining (2), (3), and (4) results in a relation between ion energy and its arrival time after the release which depends on the ion gyroradius $R_i$ and the expansion velocity $v_{exp}$:

$$t = \frac{R_i}{v_{exp}} \cdot \sqrt{\left(\arccos\left(1-\frac{2E}{E_{Max}}\right)-\sqrt{1-\left(1-\frac{2E}{E_{Max}}\right)^2}\right)^2+\left(\frac{2E}{E_{Max}}\right)^2} \tag{5}$$

Thus we would expect to observe ions in a given energy passband at a time t after the release according to relation (5). The geometry of 10- and 20-keV lithium ions is shown schematically in Figure 2.

In the presence of strong scattering of the ions the pure cycloidal motion would be destroyed. A diffuse distribution convected with the solar wind would be expected to have a velocity up to twice the solar wind value. Such a distribution can still be clearly distinguished from the solar wind. Scattering of pick-up ions may be expected either from intrinsic small scale fluctuations of the interplanetary field or from an instability driven by the ring distribution of the pick-up ions itself, as discussed by Wu et al. (1973) and recently for the specific situation of the lithium releases by Winske et al. (1985). However, during the first cycloidal period, significant scattering is not expected.

## Instrumentation and Spacecraft

The SULEICA (suprathermal energy ionic charge analyzer) instrument has been developed by the Max-Planck-Institut and the University of Maryland to measure independently the energy, mass and ionic charge of incoming ions in the energy range 5 to 270 keV/charge. The instrument combines an electrostatic deflection of entering particles with a time-of-flight measurement, and the measurement of the total ion energy in a solid state detector. The fanlike aperture covers a solid angle of 10 degrees in azimuthal and 40 degrees in elevation symmetric to the plane perpendicular to the spin axis of the satellite. The energy range of the instrument is scanned by stepping the analyzer voltage in logarithmic increments in synchronism with the spin. A more detailed description of the instrument may be found elsewhere (Möbius et al., 1985).

For the first lithium release on September 11, 1985, the instrument setting was optimized to cover only the energy range between 5 and 10 keV/charge for the first 5 minutes after release, followed by a mode in which the energy range between 5 and 160 keV/charge was scanned in steps of a factor of 2 to allow for the highest time resolution of the instrument (26 s for the six steps). For the second release

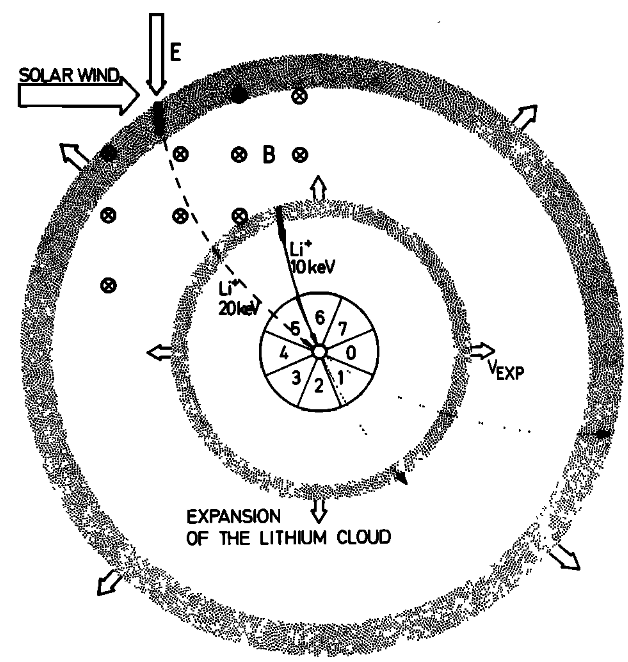


Fig. 2. Expanding Li vapor shell as origin of newly created ions which arrive at the spacecraft with 10 keV (inner ring) and 20 keV (outer ring), respectively. The ions gain energy from the $\underline{v}_{SW} \times \underline{B}$ electric field depending on the traveling distance to the spacecraft. The energy and the arrival direction are correlated. The look directions of the azimuthal sectors of the SULEICA sensor are also indicated.

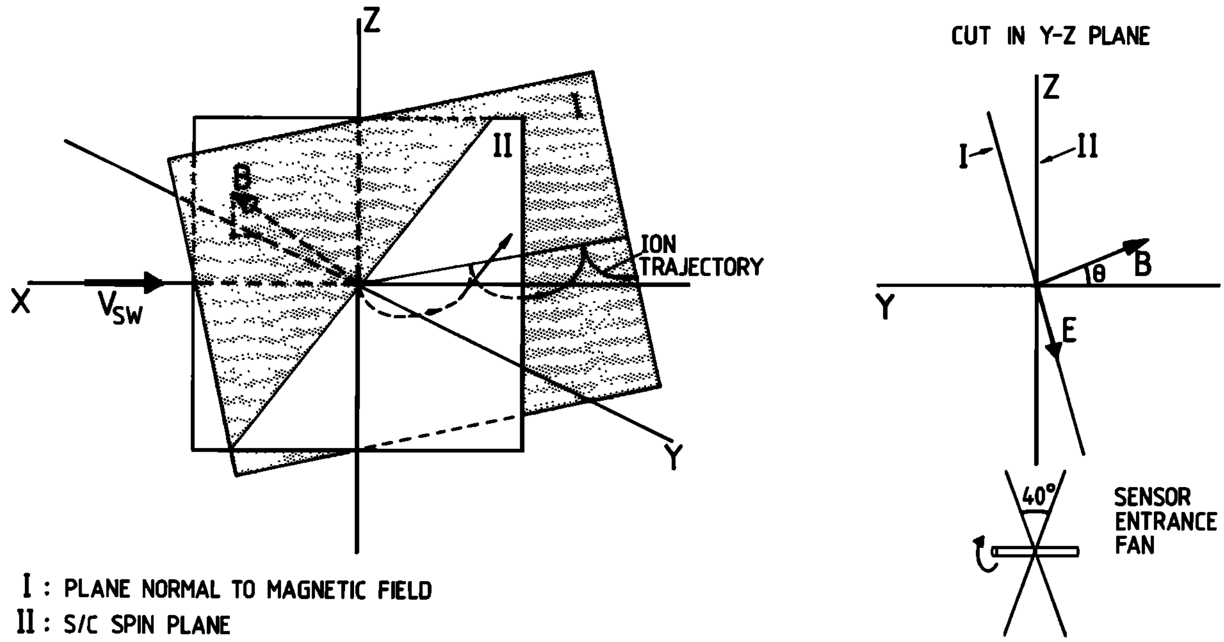


Fig. 3. (Left) Trajectory of pick-up ions in the plane perpendicular to B (I), along with the plane perpendicular to the spin axis of the spacecraft (II). The part of the trajectory parallel to the intersection line of the plane is indicated by an arrow. (Right) Cut in the yz plane along with a cut through the sensor entrance fan. The spacecraft spin axis is parallel to the y axis.

on September 20, 1985, the instrument was switched into a mode which covers the energy range from 5 to 20 keV/charge with a stepping increment of $\sqrt{2}$. For a specific energy step, ions of different mass per charge are clearly separated by their time of flight. In the low energy range of the instrument (below 40 keV total) the signal of the solid state detector does not exceed the noise level. Therefore the pulse heights of the events form a broad distribution in energy near 0 keV, and the charge states of the ions can only be inferred. However, the determination of the mass per charge (M/Q) of the ions is not affected.

The most severe condition for the detection of pick-up ions is set by the limited entrance aperture of the perpendicular to the spin axis instrument with respect to the interplanetary magnetic field direction. The situation encountered by the SULEICA instrument is sketched in Figure 3. During the time period around the two lithium releases the plane perpendicular to the spin axis of the IRM satellite was oriented almost exactly within the xz plane (II) of a GSE coordinate system. Thus the 40° by 10° aperture of the sensor scans only $\pm$ 20° above and below the xz plane. Newly created ions, which are at rest in the reference frame of the satellite, perform, due to the $v_{SW}xB$ electric field, a cycloidal motion in a plane perpendicular to the actual interplanetary magnetic field (I). Therefore pick-up ions can be observed with the SULEICA sensor along their full cycloidal path as long as the angle θ between these planes is smaller than 20°. Under these circumstances, ions should be observable with combinations of energy and arrival direction which depend on the distances of their origin from the spacecraft. However, if θ exceeds 20°, the ions can only be detected on a short section of the cycloidal trajectory, where the tangent to the curve is parallel to the intersection line of both planes. This condition corresponds to a certain phase on the cycloid, and only ions with a specific energy from a fixed arrival direction can be observed.

## Observations

The first lithium cloud was released on September 11, 1984, at 0725 UT. In Figure 4 we show two time-of-flight (TOF) versus energy event matrices accumulated over 15 minutes of data before (0700-0715 UT) and after (0740-0755 UT) the lithium release for the energy steps at 10 and 20 keV/charge.

While the matrix is empty at the location of $Li^+$ before the release, there are four $Li^+$ ions at 20 keV and two at 10 keV after the release. In addition, we observe $He^+$ ions during both time periods. Both ion species are detected only in the azimuthal sector 5 for 20 keV and in sectors 5 and 6 for 10 keV. These sectors cover the expected arrival direction of pick-up ions. As shown by G. Haerendel et al. (unpublished manuscript, 1985) and Paschmann et al. (this issue), the Li vapor cloud expanded like a hollow sphere with a maximum velocity of a few kilometers per second. In Figure 2 the vapor shell is indicated by a shaded ring for two phases of its radial expansion, which are separated in time by a factor of 2. Since the newly created Li ions originate at any instant in a limited region of space, they arrive at the satellite during a certain phase of their cycloidal path. Therefore the arrival direction and the energy of the ions are well determined. The azimuthal sectoring scheme of the SULEICA sensor is also shown in Figure 2. It is evident that pick-up ions will only arrive in sectors 5 or 6, as is indeed observed.

The temporal sequence of the events during the

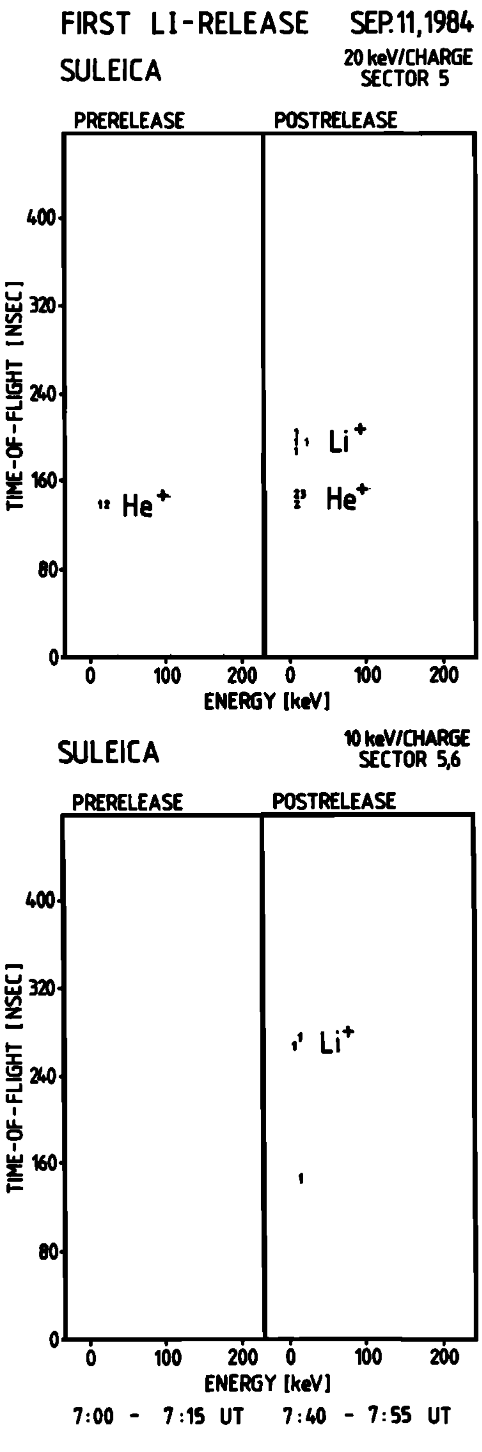


Fig. 4. Two-dimensional energy versus time-of-flight representation of ions for a 15-minute period after the first Li release and a reference period before the release. Symbols for $Li^+$, $He^+$ and M/Q = 2 are indicated. Top: 10 keV/charge. Bottom: 20 keV/charge.

first Li release on September 11, 1985, is presented in Figure 5. Shown from top to bottom is the flux of the 10-keV protons as observed with SULEICA, the density of protons with energies > 1 keV (panel 2) as obtained with the three-dimensional plasma sensor on IRM (Paschmann et al., this issue), and the elevation angle of the magnetic field in spacecraft sun coordinates (SCC) (panel 3). The next two panels show the number of ions in the mass/charge range of Li at energies between 5 and 20 keV. The observed ions are displayed in a histogram in increments of 2 minutes for all azimuthal sectors (except the sun sector 4) (panel 4) and for sectors 5 and 6 only (panel 6) (the expected arrival direction of pick-up ions). The symbols in the histogram indicate the energy for each particle, and the numbers indicate the azimuthal sectors. The lithium was released at 0725 UT as indicated by the dashed line. The flux and the density of energetic ions in the first two panels of Figure 5 indicate the presence of energetic particles upstream of the bow shock during periods when the interplanetary magnetic field was probably connected with the bow shock. During these periods, which are indicated in panel 5 by shading, the interplanetary magnetic field is mainly in an earth-sun direction (see Lühr et al., this issue) such that solar wind and magnetic field are oriented more or less parallel to each other and thus the acceleration of pick-up ions is very inefficient. The particles seen during these time periods in the TOF bins of $Li^+$ ions must be attributed to the upstream energetic particle population and probably represent heavy ions in high charge states like $Fe^{10}$ to $Fe^{12}$. Heavy ions of these charge states are known to exist in the solar wind, which is considered as the source of upstream energetic particles (Galvin et al., 1984; Ipavich et al., 1984). The upstream acceleration is further supported by the anisotropy of the population (Scholer et al., 1981) as shown in Figure 6a. The angular distribution is much weaker and clearly distinct from what we consider as the $Li^+$ "pick-up" ion population (Figure 6b). The latter particles arrive only from sectors 5 and 6, as expected for pick-up ions. A few of the ions observed during the upstream events after the release at 0725 UT might still be Li ions which have been reflected at the bow shock and accelerated like solar wind ions. However, no distinction between Li and other ions is possible, since during the upstream event before the release (0715-0728 UT) ions in the Li range were also observed.

During the main period after the Li release between 0728 and 0820 UT, upstream particles were absent except during a short time between 0755 and 0758 UT when the magnetic field was nearly perpendicular to the solar wind direction and thus favorable for the acceleration of pick-up ions. During this time period, ions in the mass per charge range of Li were detected only between 0740 and 0755 UT and around 0803 UT. All these ions except a single ion at 0733 UT were seen in sectors 5 and 6 where pick-up ions from the release were expected. During the reference period undisturbed by upstream particles between 0700 and 0715 UT before the release, not a single count was registered in the Li channels. Thus the ions shown in the pulse height matrices in Figure 4 could be unambiguously identified as Li pick-up ions from the release.

Although the favorable situation for accelerating pick-up ions lasted from 0728 to 0823 UT, the time for favorable observational conditions was much shorter (panels 3 and 7). The reason for this behavior is shown in panel 3 of Figure 5. The elevation of the magnetic field in spacecraft coordinates is below 70° most of the time except during the periods around 0745 and 0805 UT when the Li ions are observed. Due to the unfavorable orientation of the

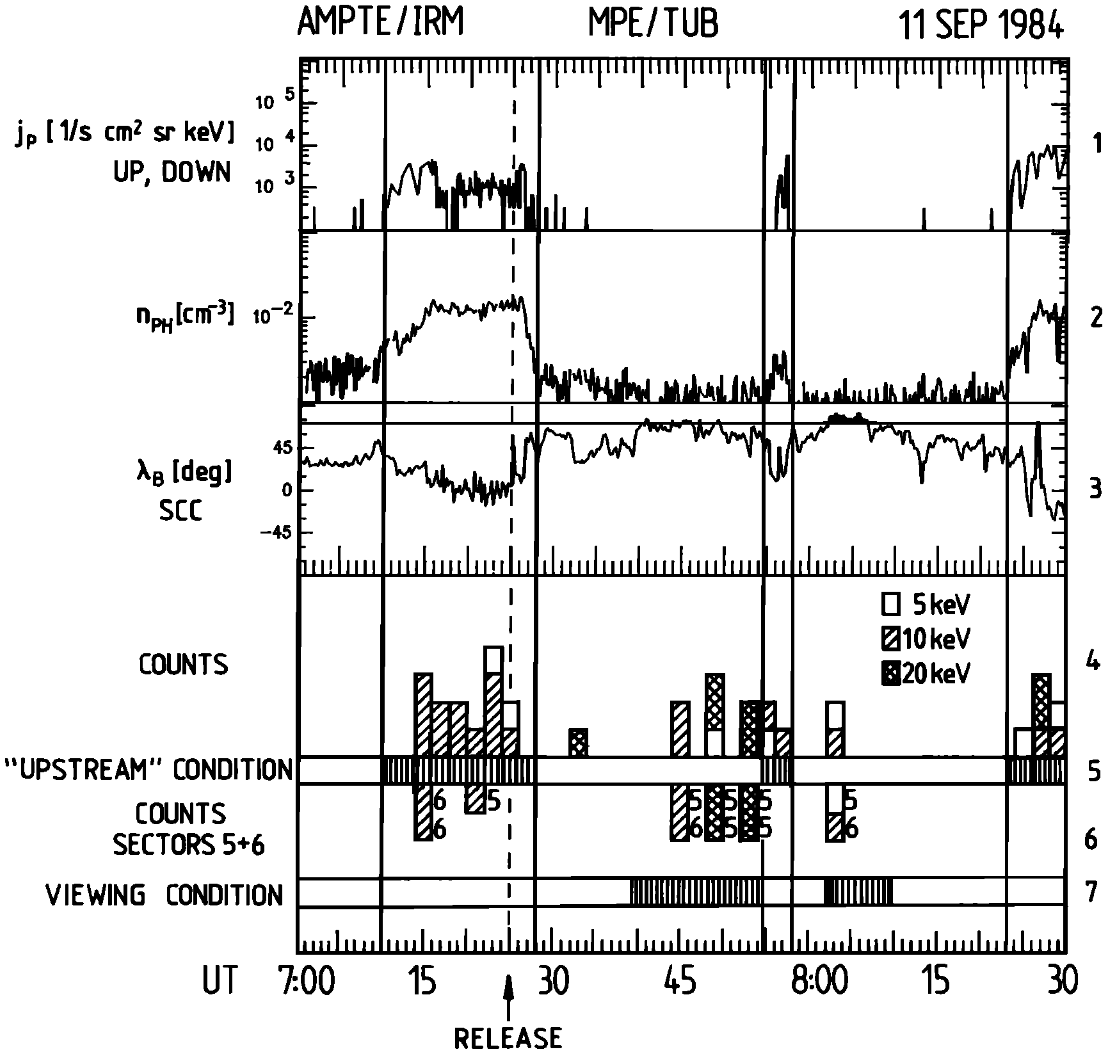


Fig. 5. Flux of 10-keV protons except sun sector (panel 1), density of protons with E > 1 keV (panel 2), elevation angle of the magnetic field $\lambda_B$ in spacecraft coordinates (panel 3), and registration of ions in the Li channels (panel 4) versus time for a 90-minute period around the first Li release. Ions arriving from sectors 5 and 6 are shown in panel 6. The time of release is indicated by an arrow. The flux increases of the 10-keV protons and density of E > 1 keV protons indicate the occurrence of upstream ions. The observation condition for pick-up ions according to the acceptance fan of the SULEICA sensor is indicated by the line at 70° in panel 3. The shaded areas in panels 5 and 7 indicate the overall period with favorable conditions for "upstream" particles and for viewing pick-up ions, respectively.

spacecraft relative to the interplanetary magnetic field during the remaining time periods, ions could reach the aperture only on part of the downleg of the cycloid (which was parallel to the intersection line between the spinning plane of the IRM spacecraft and the plane perpendicular to the magnetic field; cf. Figure 3). This portion of the cycloid is populated with Li ions which originate at a distance of ≈ 4 to 5 ion gyroradii (≈15,000 km). Such distances from the spacecraft are reached by the expanding cloud not before 90 minutes after the release, at which time the Li cloud was too dilute for observation. Altogether a total of four counts at 20 keV, three counts at 10 keV, and one count at 5 keV could be clearly identified as Li pick-up ions. No ions with energies 40 keV or higher were observed.

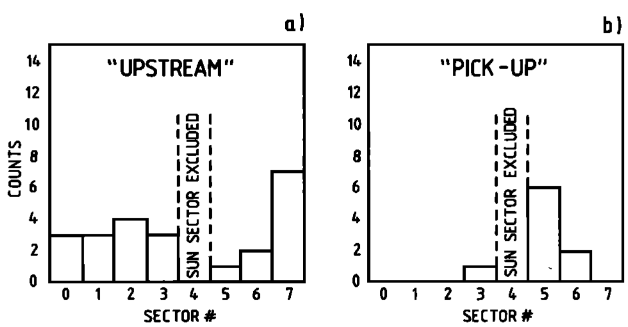


Fig. 6. Angular distribution in spacecraft azimuth of ions observed in the $Li^+$ bin of the pulse height matrix (a) favorable for conditions upstream particle acceleration and (b) magnetic field orientation with good viewing condition. The sun sector is excluded.

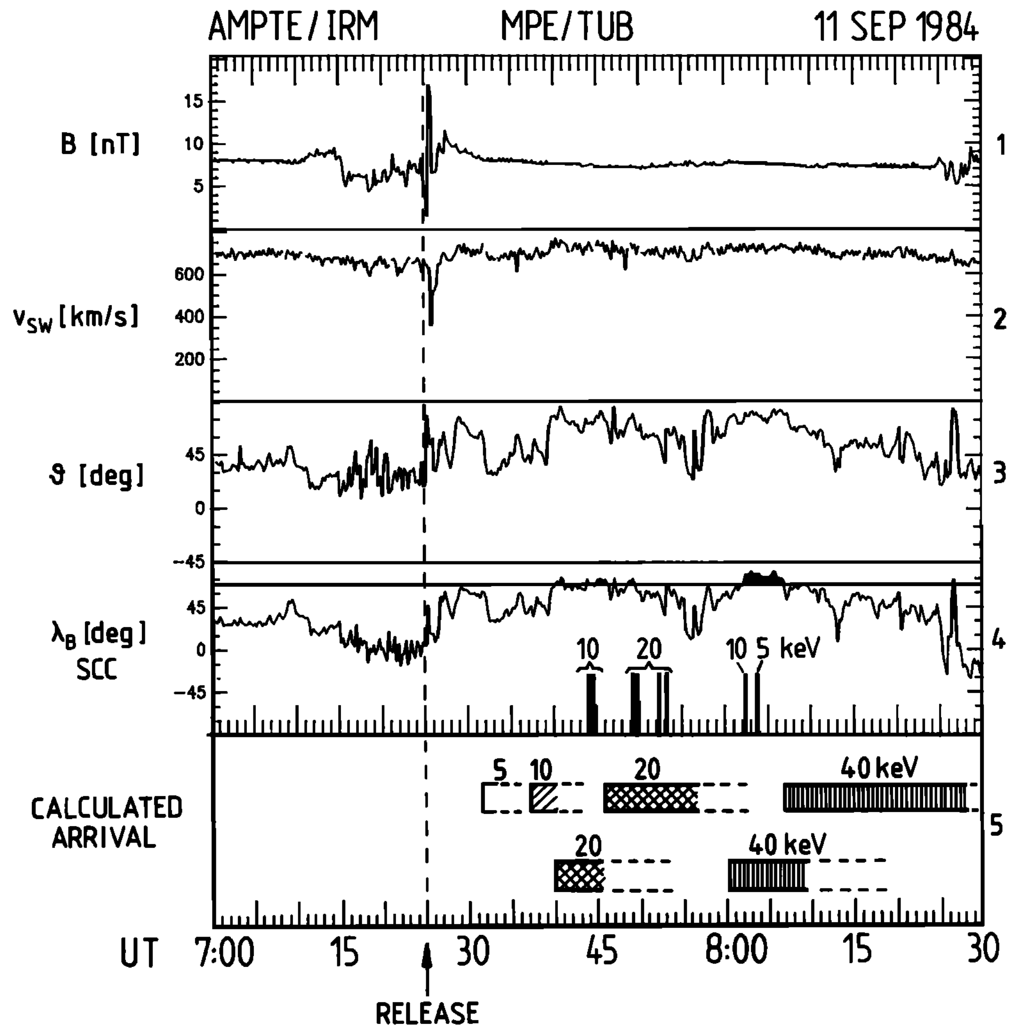


Fig. 7. From top to bottom: magnetic field value (panel 1), solar wind velocity (panel 2), angle between magnetic field and solar wind ϑ (panel 3), elevation angle of magnetic field in spacecraft coordinates $\lambda_B$ and occurrence of Li pick-up ions versus time (panel 4). From the values of the first three panels, arrival times for 5-, 10-, 20-, and 40-keV Li ions have been calculated under the assumption of lithium expansion velocities between 1.8 and 2.7 km/s (upper bars in panel 5), and velocities ≤ 3.8 km/s (lower bars in panel 5).

A similar analysis of the SULEICA pulse height data and of the observation conditions has been performed for the second Li release on September 20, 1985, at 0956 UT. During the whole period the magnetic field is nearly perpendicular to the solar wind velocity, and no upstream ions are observed. Because the angle between the spin axis and the magnetic field is well beyond 20° for the whole period and the intersection line of the basic planes (Figure 3) is only parallel to the ion trajectory in the down leg of the cycloid, the visibility condition for Li ions was poor. Favorable observational conditions were found only more than one hour after the release. At this time the ion flux was well below the detection threshold of the instrument. Therefore it is not surprising that no Li ions were observed with the SULEICA sensor during the second release.

## Discussion

The temporal evolution of the pick-up ion distribution in energy after the release can, in principle, be used to determine the expansion velocity of the lithium vapor cloud. This method was successfully applied at low ion energies (< 1 keV), particularly for the second AMPTE lithium release on September 20 by Paschmann et al. (this issue) and Coates et al. (this issue). Here relation (5) between energy and expected observation time for an assumed shell-like structure of the cloud was used in the linear approximation

$$t = \frac{R_i}{v_{exp}} \cdot \frac{2E}{E_{Max}} \tag{6}$$

For the Li release on September 20, Paschmann et al. (this issue) obtained a maximum expansion velocity of 3.8 km/s using the plasma instrument on the IRM spacecraft, and Coates et al. (this issue) obtained on the UKS spacecraft a velocity range for the particles from the Li shell between ≈ 2 and 3.1 km/s. In order to be observable the Li ions at higher energies (i.e., 5 to 40 keV) the ions have to travel a substantial fraction of the cycloidal trajectory (cf. Figure 2). In this case, relation (5) rather than the linear approximation describes the situation correctly. The magnetic field strength B, the solar wind speed $v_{sw}$, and the angle $\vartheta$ between interplanetary magnetic field and solar wind are taken from Figure 7 as input parameters to relation (5). By using the actual values from panels 1 through 3 and the measured arrival time of each ion the expansion velocities were calculated. The values range from about 2.25 km/s for the 20-keV ions to 1.4 km/s and 0.65 km/s for the 10-keV ions at 0744 UT and 0802 UT, respectively.

In panel 5 of Figure 7 we have plotted the expected arrival time periods for 5, 10, 20, and 40 keV for two different regimes of expansion velocities. The lower set of bars correspond to the upper limit of the expansion velocity of 3.8 km/s as reported by Paschmann et al. (this issue). Here we would expect to observe 20-keV Li ions between 0740 and 0745 UT, when the viewing conditions for the instrument are favorable; 40-keV ions should have been observed after 0802 UT for about five minutes, when the viewing conditions were even better. In spite of the higher sensitivity of the 40-keV/e range of the instrument relative to the 20-keV/e range (by a factor of 3) we did not observe a single Li ion count. We therefore conclude that an expansion velocity of the main distribution in excess of 2.7 km/s is not compatible with our observations. The expansion of the lithium cloud may not be perfectly isotropic such that different expansion velocities are measured for different arrival directions of the ions. The values may also vary slightly from release to release. It should be noted that the viewing conditions of the instrument with respect to the interplanetary magnetic field orientation play an important role for the observation of Li ions and thus can be taken as an indication that pick-up ions occupy a very limited phase space and that scattering was indeed negligible on their first fraction of the cycloid. Otherwise we should have detected those ions also beyond the observation windows and within other sectors.

The set of arrival times in panel 5 (of Figure 7) for a velocity range below 2.7 km/s is compatible with our observations in view of the fact that 20-keV/e ions are observed at the expected time, and that the absence of 40-keV/e Li ions can be explained by the unfavorable observing conditions. The arrival of 10- and 5-keV ions after the bulk material, however, indicates the presence of a rather high neutral density also in the interior of the Li vapor cloud. This is also supported by the observations of Paschmann et al. (this issue) and Coates et al. (this issue).

An estimate of the absolute lithium flux from the SULEICA count rate is difficult, since the viewing conditions of the sensor are fulfilled only temporarily. Assuming an integration time of about 5 minutes - the time within which the 20-keV Li ions were detected - for the bulk of the 20-keV ions results in a particle flux of $j = 26$ ions/cm$^2$ s. The expected ion flux from the cloud can be estimated (G. Haerendel et al., unpublished manuscript, 1985) from

$$j = \frac{3 \cdot N \cdot \nu_i}{4\pi (v_{exp} \cdot t)^3} \cdot e^{-\nu_i t} \cdot \Delta R \qquad (7)$$

where N is the total number of Li atoms in the cloud, $\nu_i$ the ionization frequency, and $\Delta R$ the fraction of the radius of the shell-like cloud from which ions arrive within the energy band of the instrument. Since $E \sim R$ to a zero-order approximation and $\Delta E/E \approx 0.1$ for the SULEICA sensor, we may use $\Delta R/R \approx 0.1$. For the flux estimate the vapor shell has been treated like a full sphere, since the ratio of total shell thickness and radius is $\approx 0.3$ for the assumed range of expansion velocities and thus the error in flux is small. In addition, part of the lithium is found in the interior of the sphere. Using a value of $3\,N\,\nu_i/4\pi v_{exp}^3 = 5.6\text{x}10^4$ cm$^{-3}$ s$^2$, and assuming $\nu_i = 1/3600$ s$^{-1}$, a flux of $j \approx 600$ ions/cm$^2$ s at 20-keV is estimated. This exceeds the observed flux by a factor of 20. This discrepancy may be explained as follows: as can be seen from Figures 5 and 7, the favorable observation condition of the instrument is only occasionally fulfilled. Thus the integration time of 5 minutes may be greatly overestimated. Furthermore, the ions reach the time-of-flight spectrometer at the edge of the acceptance fan where the detection efficiency is substantially reduced compared to the mean value.

In conclusion, we have observed Li pick-up ions from the first Li release on September 11, 1985, at 0725 UT, which are compatible with expansion velocities of the bulk material of the cloud below 2.7 km/s, a value which is somewhat lower than those given by Coates et al. (this issue) and Paschmann et al. (this issue) for the second Li release on September 20, 1985. Ions from a more dilute population in the interior of the cloud are also seen. Scattering of the ions on the first few thousand kilometers of their trajectory does not seem to be important.

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