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Pickup ions ($E_{0^+} > 55$ keV) measured near Mars by Phobos-2 in February/March 1989

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Abstract. The Soviet spacecraft Phobos 2 reached Mars on 29 January 1989. The onboard solar low energy detector (SLED) recorded particles of solar and planetary origin while in elliptical and circular orbits about the planet. Enhanced fluxes were identified, particulary during periods of spin stabilisation, superimposed on the general particle intensity time profile. These latter fluxes are interpreted here, using backup evidence from simultaneous solar wind and magnetic field measurements recorded on the same spacecraft, to have constituted pickup ions (O^+, O_2^+) with $E_{0+} \geq 55$ keV.

Introduction

The Phobos 1 and Phobos 2 spacecraft (S/C) to Mars and its moon were launched from Baikonur in July 1988. Only Phobos 2 reached Mars. Energetic particle measurements (in the range 30 keV to a few tens of MeV) were made onboard this spacecraft by the solar low energy detector (SLED) instrument during the approximately 200-day cruise phase, as well as in the close planetary environment. In the latter period of observation, four elliptical orbits of pericentre 867 km and apocentre ~83 550 km, an elliptical orbit of high pericentre and, from 20 February, 1989, 114 circular equatorial orbits with initial $R=$ 9700 km and final $R=9100-9650$ km were performed, (Sagdeev and Zakharov, 1989).

It is the purpose of this paper to seek to identify in the SLED data, superimposed on the general particle intensity time profiles, signatures attributable to pickup ions. Such pickup ions are predicted to be present near Mars by calculations using the model of Luhmann and Schwingenschuh (1990) and of Luhmann (1990). They have already been detected at Venus (Mihalov and Barnes, 1981), and at comets Giacobini-Zinner (Hynds *et al.*, 1986) and Halley (McKenna-Lawlor *et al.*, 1986). Simultaneous onboard measurements of the magnetic field near Mars made by the MAGMA instrument (Riedler *et al.*, 1989; Roatsch *et al.*, 1989), and of the solar wind by the toroidal analyser and spectrometer TAUS (Rosenbauer *et al.*, 1989), were made available to support this study by the experimenters.

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Experimental description

The SLED instrument (for a detailed experiment description see McKenna-Lawlor *et al.*, 1990) uses semiconductor detectors in two different telescopes which are directed 55° westward to the S/C-sun line in order to avoid the direct impact of sunlight. The line-of-sight direction agrees approximately with the direction of the nominal interplanetary magnetic field. The front detector telescope 1 (Te1) is covered with 15 μg/cm² aluminium, whereas telescope 2 (Te2) uses an additional aluminium foil of 500 μg/cm² which absorbs protons of energy less than 350 keV but allows the detection of 35–350 keV electrons. Thus, the count rate difference between the open telescope (Te1) and Te2 allows differentiation between proton and electron fluxes. The opening angle of the telescope apertures was ±20°.

The geometric factor of both telescopes was 0.25 cm² ster, and the time resolution was about 240 s

The energy channels of Te1 are listed in Table 1 for protons and for the two lowest oxygen ion channels.

Oxygen ions whose energies exceed 55 keV penetrate 15 μg/cm² aluminium and are recorded by semiconductor detectors (Keppler, 1978). The Phobos S/C was nominal-

Table 1. Energy channels of SLED, Te1

Ch 1	34– 51 keV p	55– 72 keV O
Ch 2	51–202 keV p	72–223 keV O
Ch 3	202–609 keV p	
Ch 4	0.6– 3.2 MeV p	p = protons
Ch 5	3.2– 4.5 MeV p	O = Oxygen
Ch 6	> 30 MeV p	

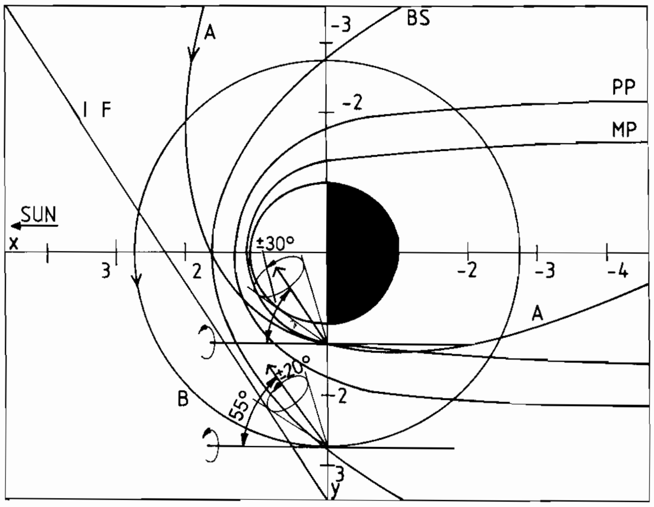

Fig. 1. Encounter of the Phobos 2 S/C with Mars and its moon Phobos. Shown are a part of an elliptical orbit (*A*) and the circular orbits (*B*). BS = bowshock, PP = planetopause, MP = magnetopause, IF = nominal interplanetary magnetic field. The line-of-sight directions of SLED for both orbits are indicated. Pickup ions were observed near Mars along the elliptical and circular orbits, especially during periods with spin stabilisation of the S/C

ly 3-axis stabilised, but after orbit correction maneuvers it rotated slowly with periods of 440–700 around the S/C-sun line (x-axis). Intervals with spin motion were more suitable for the detection of pickup ions, because a larger part of the sunward-directed space (55° ± 20°) could be studied than was possible during 3-axis stabilisation. Figure 1 presents the encounter situation of the Phobos 2 S/C with Mars.

Observations

Figure 2 shows an overview of particle measurements obtained during the elliptical (30 January–15 February 1989) and circular orbits (20 February–26 March 1989) of Phobos around Mars. During that period, solar particles from the active sun were present in abundance and pickup ions can only be identified as enhancements above this background flux. The foil-covered Te2 did not record such enhancements, indicating that Te1 detected low energy ions rather than enhanced electron fluxes.

These were particularly noticeable during the first and second pericentre passages of the elliptical orbits, and also during the circular orbits from 1–3 March, 1989 when Phobos-2 was spin-stabilised. Flux enhancements (designated in Fig. 2 by horizontal bars; PC = pericentre) appeared above the solar particle background in the data of Te1, channels 1 and 2 (see the corresponding energies listed in Table 1).

Figure 3 shows those measurements pertaining to the first pericentre in higher time resolution, together with the concomitant magnetic field data obtained by the MAGMA experiment (Riedler *et al.*, 1989). As shown, the azimuth angle varied over the relevant interval between 270° and 90° (i.e. the interplanetary magnetic field was perpendicular to the solar wind direction for part of the time). Only the particle fluxes in the first two energy channels were enhanced from 1 February ~15:00 UT ($R \simeq 7.6$ R_M) to 2 February ~08:00 UT ($R \simeq 17$ R_M). At greater distances, when Phobos-2 was 3-axis stabilised, some sporadic enhancement were also recognised in the data.

Figure 4 shows the internal 1–2 March 1989, when Phobos-2 was in a circular orbit ($R = 2.8$ R_M) around Mars. From 00:00 to 10:00 UT on 1 March, Phobos-2 was 3-axis stabilised and did not detect pickup ions. The short vertical lines in the upper part of Fig. 4 designate azimuth angles $\alpha = 0°$ of the orbital periods. Bowshock crossings are indicated by long vertical lines. The apparent modulation results from the fact that the spin axis performed a precession around the momentum axis. The precession angle reached in different periods covered a wide range of values and was obviously not controlled. General enhancements which are interpreted as pickup ions (and some noise in the channels 3 and 4) appeared in channels 1 and 2 (16:00 UT, 1 March–24:00 UT, 2 March).

On 1 March between 17:00 and 18:00 UT (azimuth angles 158°–200°) when Phobos-2 passed through the tail side, small outflowing ion fluxes can be recognised (Lundin *et al.*, 1989). The record of 2nd March (Fig. 4) shows a further phenomenon. Spikes appear during the interval 03:30–04:30 UT ($\alpha = 271°–318°$); at $\simeq$15:00 UT ($\alpha = 63°$) and at $\simeq$19:00 UT ($\alpha \simeq 245°$), i.e. on both sides of the bowshock, the position of which can be recognised by the characteristic signatures of the tail magnetic field [see the lower part of Fig. 4, which shows B_{total} (BT)]. We tentatively identify the flux enhancements to represent low energy particles appearing outside and inside of the bowshock. The spikes observed directly during the bowshock crossings have been interpreted by Afonin *et al.* (1991) as shock-accelerated particles.

In Fig. 5 examples of flux measurements during 3-axis stabilisation are presented for pericentre passage No. 3 on 8 February 1989 and for circular orbits from 12 March 1989. The pericentre passage shows a maximum at ~06:00 UT ($\alpha = 76°$), followed by a minimum at 06:10 UT ($\alpha = 106°$). Pickup ions cannot be recognised. On 12 March (Fig. 5, right side) during 3-axis stabilisation, spikes again appeared close to the bowshock passage at 00:10 UT ($\alpha = 94°$) and at 16:00 UT ($\alpha = 92°$), followed by a minimum which also appeared in the data of channels 3 and 4 at 00:30 UT ($\alpha = 110°$) and at 16:30 UT ($\alpha = 108°$). Such decreases have been explained by Afonin *et al.* (1989, 1991) as produced due to energy-related particle shielding by Mars.

Figure 6 a, b depict solar wind measurements obtained by the TAUS experiment on board of Phobos-2. The solar wind velocity during the period 1–5 February was 500–700 km/s and, during the circular orbits in the interval 1–5 March 1989, 500–600 km/s. When Phobos-2 entered the magnetosheath, the solar wind velocity decreased whereas the plasma density and temperature increased (and vice versa when the magnetosheath was exited). The gaps in the central tail region indicate that no solar wind protons were present.

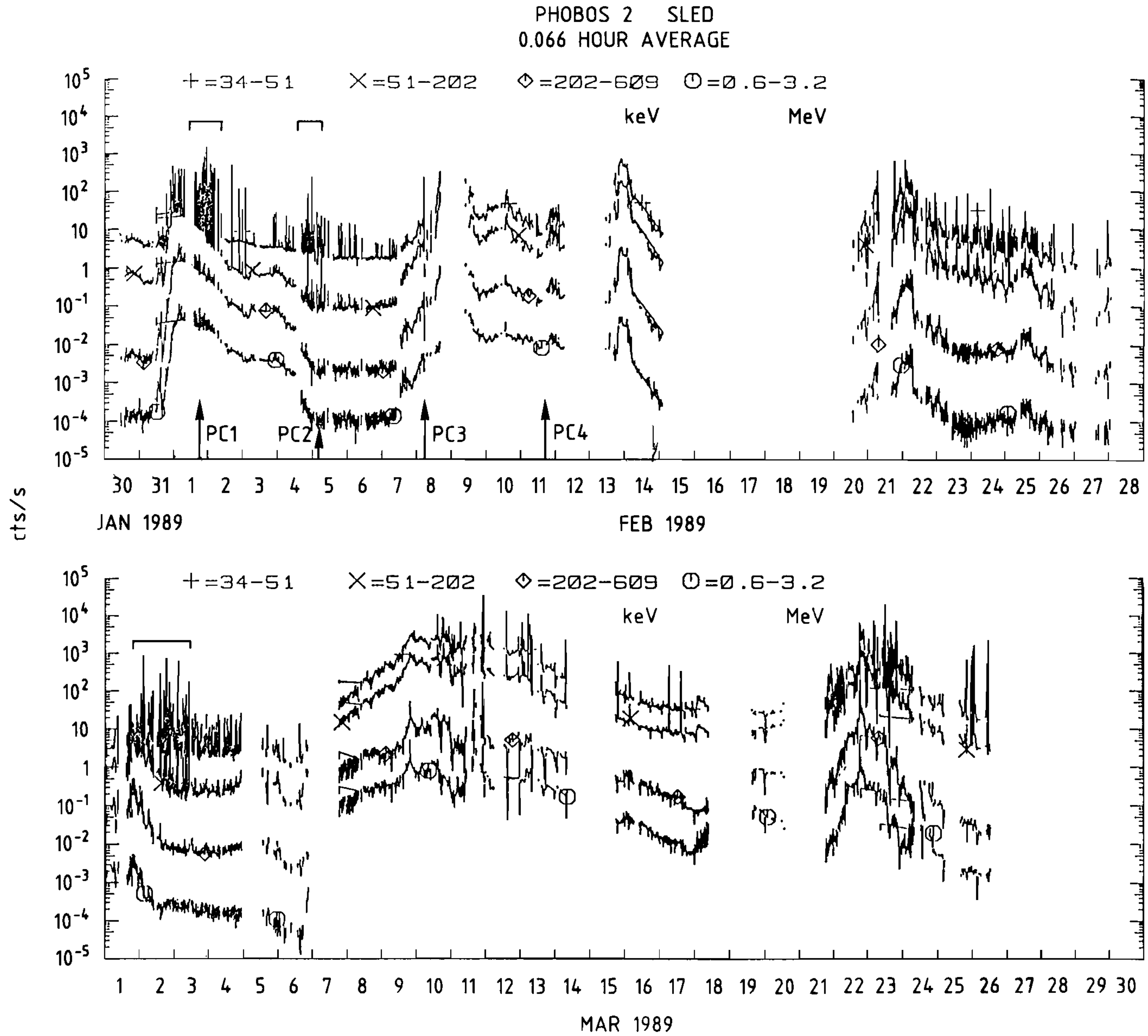

Fig. 2. Overview measurements from the first 4 channels of the open telescope (Te1) during the elliptical (30 Jan–15 Feb) and circular orbits (20 Feb–26 March 1989). Intervals with pickup ions are designated by *horizontal bars*. PC1, PC2, etc. refer to the first pericentre passage, second pericentre passage, etc.

Discussion

Since Mars has a lower gravity than that of Earth and possesses no significant internal magnetic field, interesting interaction effects between the solar wind and the extended exosphere of Mars could be observed by the Phobos-2 S/C from February to March 1989. In connection with this, Lundin *et al.* (1989, 1990) found with the automatic space plasma experiment with a rotating analyser ASPERA that Mars loses $3 \cdot 10^{25}$ oxygen ions/s ($E = 0.25 - 25$ keV/q) in the tailward direction. The TAUS experiment (Rosenbauer *et al.*, 1989) detected a similar loss rate, $2 \cdot 10^{25}$ O^+/s. In recent papers, Ip (1988, 1990) studied the hot oxygen corona of Mars and found, for the time of the Phobos-2 encounter, in 1989 during solar maximum conditions, that the non-thermal escape of exospheric oxygen from the sunlit hemisphere is comparable with the loss rate measured in the Martian magnetotail, namely $1.6 - 3.2 \cdot 10^{25}$ O^+/s. The atomic oxygen fragments, resulting from the dissociative recombination of O_{2+}, have an energy of 3.5 eV (the gravitational binding energy of Mars is 2 eV) and are therefore able to reach large distances from the planet. The fast atomic oxygen corona of Mars is resultingly deemed to be much more extensive than was previously assumed and the non-thermal escape of oxygen is seen to be a very important associated loss process.

The model calculations by Ip (1990), predict for the orbit of Phobos (2.8 R_M) a density of 100–200 O/cm^3 with, in contrast, $\simeq 30$ O/cm^3 at a distance of 10^4 km

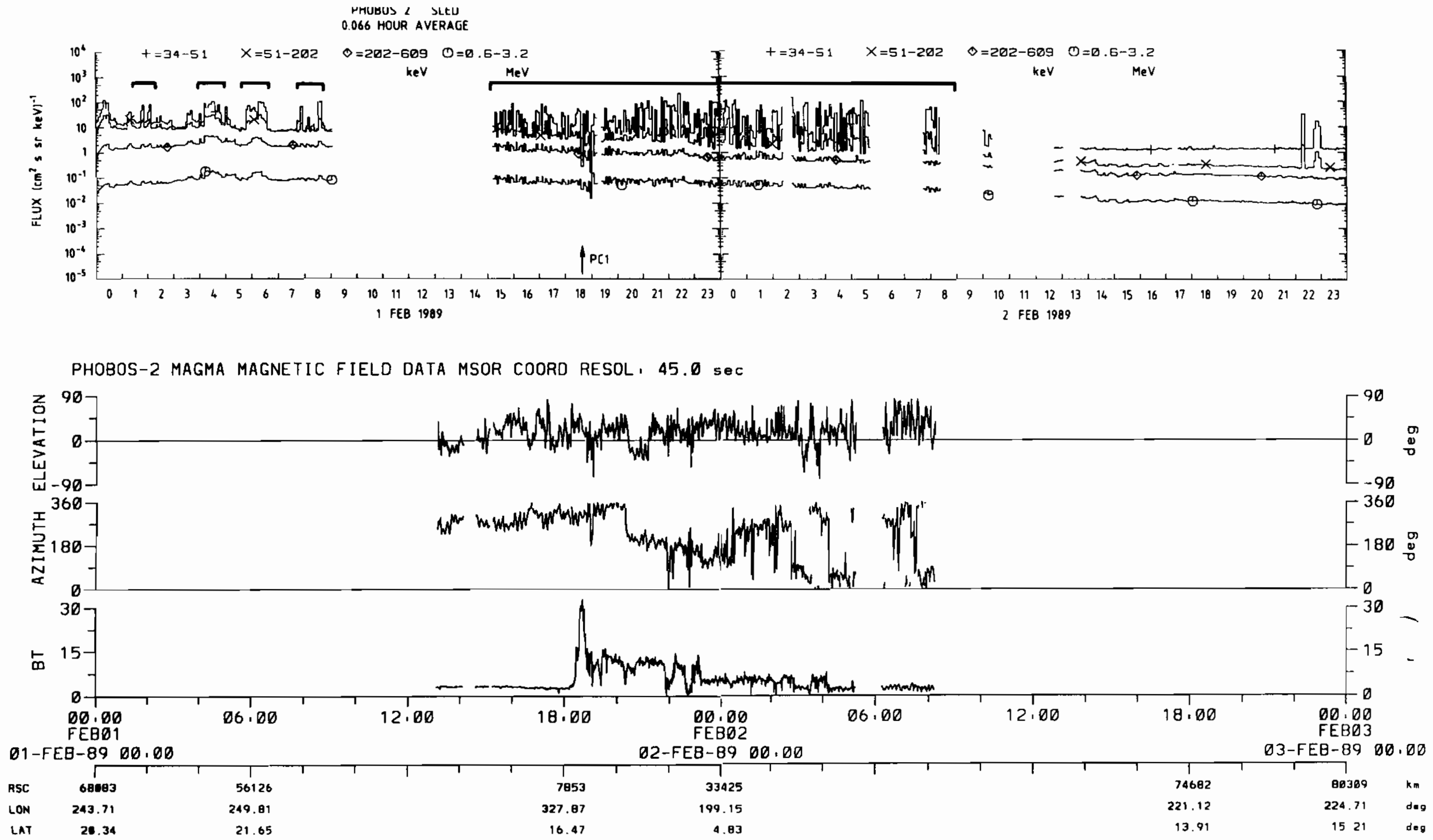

Fig. 3. Pickup ions (*horizontal bars*) of the first pericentre (PC1) passage (1 Feb 1989) with corresponding magnetic field measurements in high time resolution. Channels 1 and 2 are enhanced. The S/C was spin-stabilised during the period 1 Febr 15:00 UT–2 Feb 11:00 UT

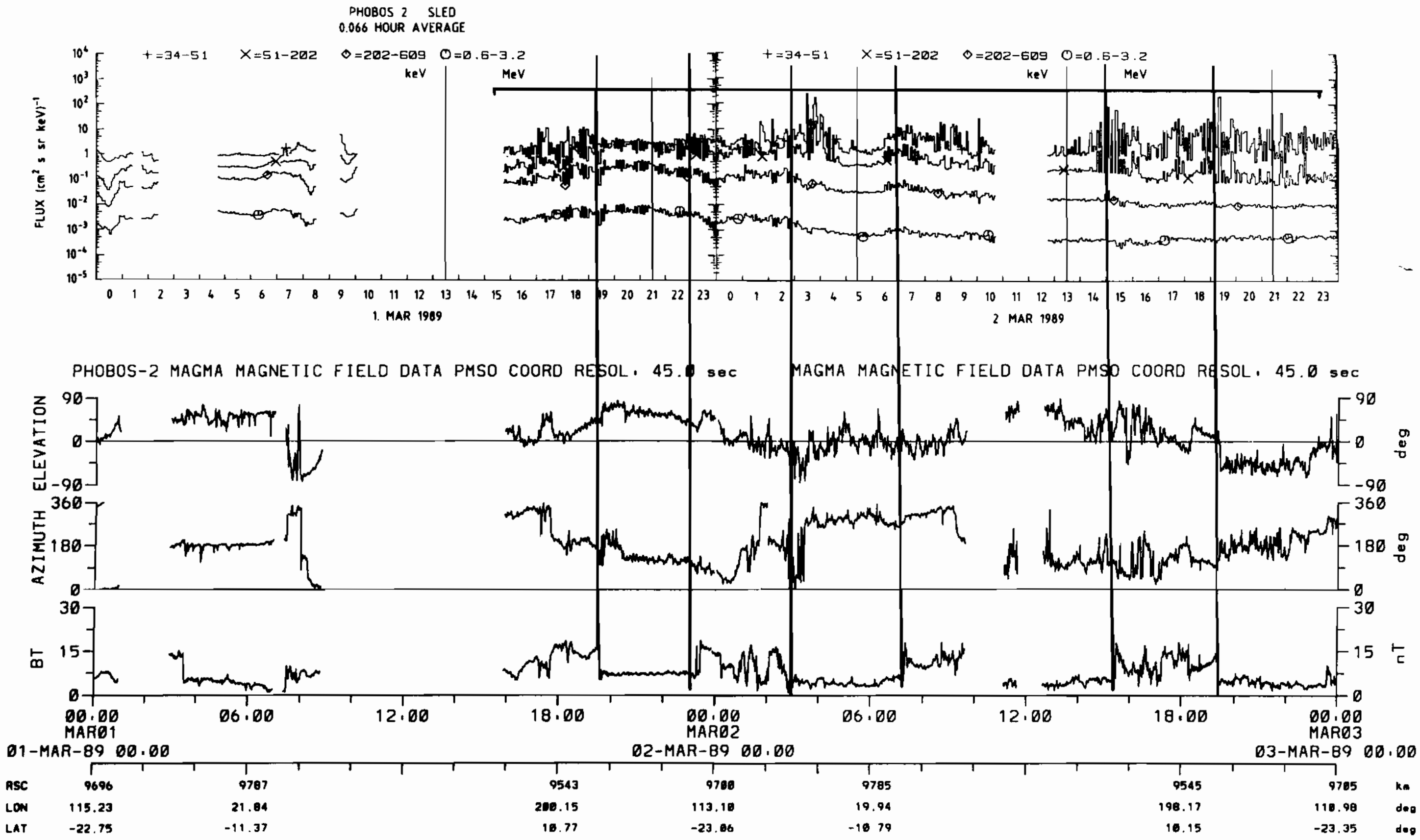

Fig. 4. Pickup ions (*horizontal bars*) measured during circular orbits with spin stabilisation (1 March 15:00 UT–2 March 24:00 UT) and magnetic field data. Again, channels 1 and 2 are enhanced. At the inbound and outbound side of the bowshock [see lower part B_{total} (BT)] spikes appear in addition. The *short vertical lines* represent azimuthal angle $\alpha = 0°$ of the new orbit (*upper part*), the *long vertical lines* are in- and outbound crossings of the bowshock

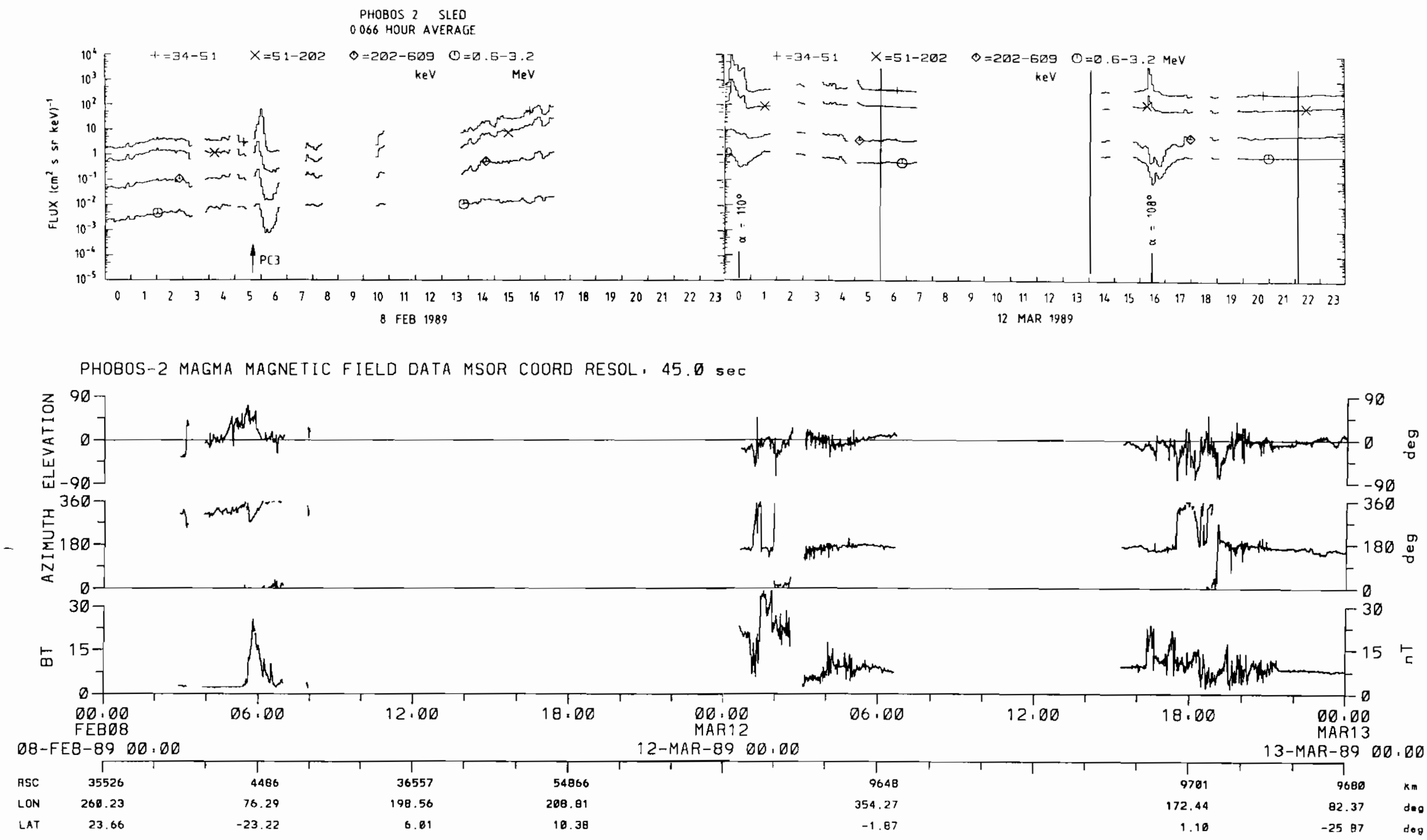

Fig. 5. Partical and magnetic field measurements obtained during 3 axis stabilisation of Phobos-2 (8 Febr and 12 March 1989). No pickup ions can be seen, but enhancements in channel-1 and 2 and decreases in channels 3 and 4

from the planet. An extrapolation of Ip's (1990) Fig. 3 results results in a density of $\sim 10^{-1}$ O/cm^3 at a distance of $\approx 6 \cdot 10^4$ km from Mars. The predicted gas and dust rings of the moons Phobos and Deimos (Ip and Banaszkiewicz, 1990) also contribute to the density of the oxygen ions. It can thus be expected that small intensities of oxygen ions ($\sim 10^{-1}$ O/cm^3) should be present at large distances ($5-6 \cdot 10^4$ km) upstream of Mars. Such oxygen ions can be picked up by the convection electric field $E = -V \times B$ of the solar wind and become accelerated to twice the solar wind velocity in the antisunward direction. The corresponding maximal energy is given by

$$E = 2M \cdot V^2 \cdot \sin^2 \vartheta \qquad (1)$$

where M represents the mass of the ions, V is the solar wind velocity and ϑ is the angle between solar and magnetic field direction. The solar wind velocity as measured by the TAUS experiment (see Fig. 6) was 500–700 km/s in February and March 1989. Table 2 shows, for H^+, O^+, O_2^+ and CO_2^+ ions, the calculated maximal energies for $\vartheta = 90°$ and $V = 500$ and 700 km/s. O^+, O_2^+ and CO_2^+ ions should be detectable at the calculated energies in channels 1 and 2 of the open telescope of SLED (compare Tables 1 and 2).

Application of the $\frac{dE}{dx}$ versus E-method for the particle identification process is not possible since the expected oxygen ions do not have enough energy to penetrate the SLED front detector of 100 μm thickness. Thus only the total energy of the pickup ions can be determined. Since

Table 2. Energy of pickup ions

V km/s	H^+ keV	O^+ keV	O_2^+ keV	CO_2^+ keV
500	5.25	100	200	275
700	12.25	196	392	539

CO_2^+ has a smaller scale height than the lighter ions, it is assumed that mainly O^+ and O_2^+ ions were detected by SLED.

Energy spectra and pitch angle distributions for such ions as a function of distance from Mars were calculated by Luhmann and Schwingenschuh (1990) and by Luhmann (1990). The highest particle energies (40–60 keV) were predicted to appear at large tailward distances from Mars. In the model calculations by Luhmann (1990), it was found that the most energetic pickup ions can be expected in the outer magnetosheath and the adjacent solar wind.

For the detection of pickup ions with Te1 of SLED, the following conditions are favourable:

1) The spacecraft should be spin-stabilised around the x-axis (the S/C sun line) because, in this case, a larger part of the sunward hemisphere can be monitored by SLED than is the case in the 3-axis stabilised condition.
2) The solar wind speed should be high so that pickup particles can be significantly energized.

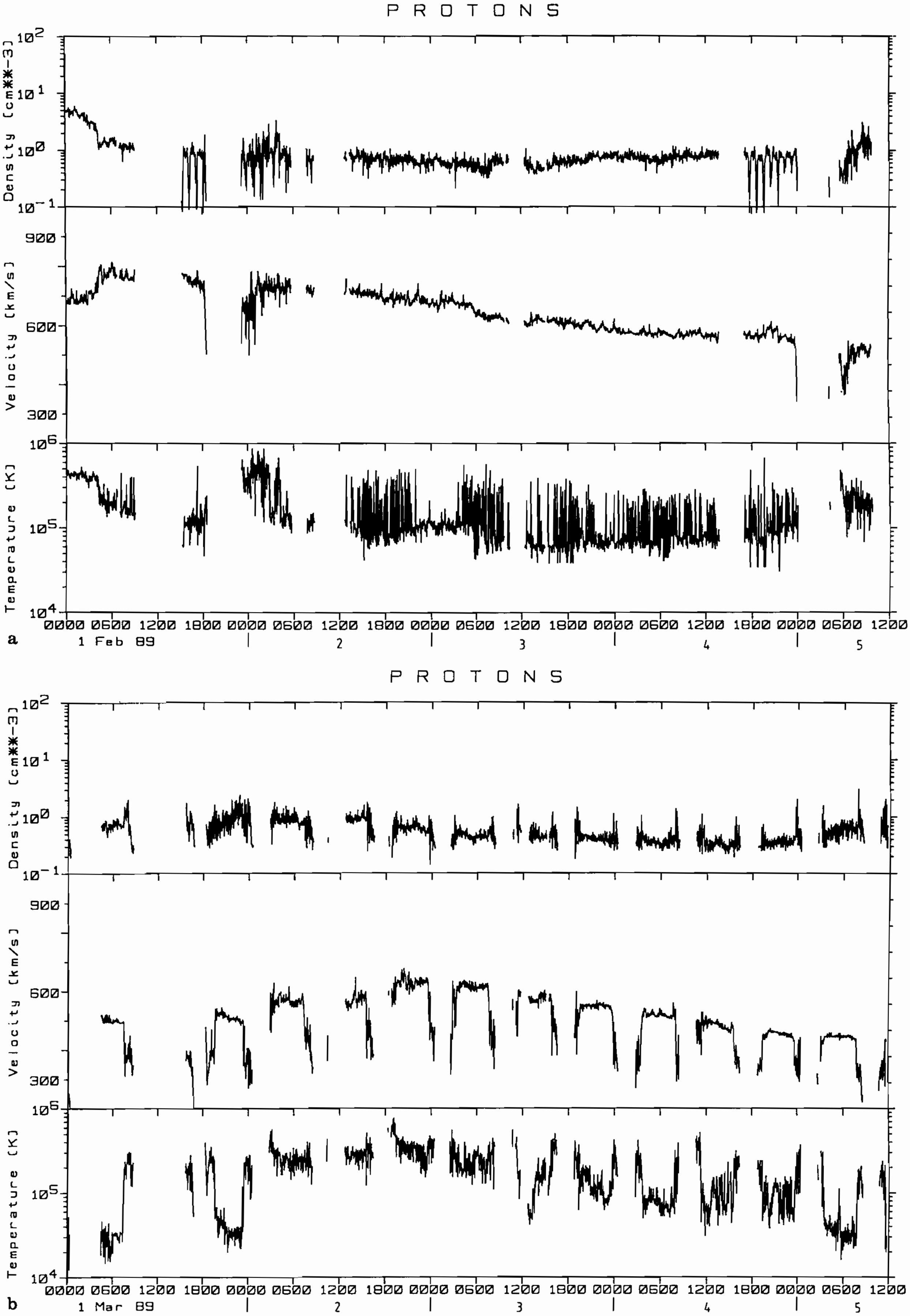

Fig. 6. **a** Solar wind measurements (density, velocity and temperature) of the TAUS experiment during elliptical orbits from 1–5 February 1989. A high speed solar wind stream ($V=500$–800 km/s) was measured. **b** Solar wind measurements of the TAUS experiment during circular orbits from 1–5 March 1989. The solar wind speed varied between 500–630 km/s. The magnetosheath passages were characterized by an increase of the density, a decrease of the velocity and an increase of the plasma temperature. The gaps in the central tail region indicate that no solar wind protons could be detected

3) The azimuthal angle of the magnetic field should be around 90° or 270° because $\sin^2 \vartheta$ in Eq. 1 is about 1.

The above-mentioned conditions were fulfilled for the intervals covered by the records presented in Figs. 2, 3 and 4, and the fluxes detected superimposed on the general particle counts are therefore interpreted to constitute, most probably, O^+ and O_2^+ ions. From the data, an excess count rate of about 100 cts/s can be derived. At the Tel geometric factor of 0.25 cm^2 ster, this corresponds to 400 O^+/cm^2 s ster or $5 \cdot 10^3$ O^+/cm^2 s. Assuming 100 keV O^+ ions of $v = 1.09 \cdot 10^8$ cm/s velocity, one finds the particle density of the source region to be $4.6 \cdot 10^{-5}$ O^+/cm^3. The gyroradius of a 100 keV O^+ ion in a 3 nT magnetic field is $R = 6.08 \cdot 10^4$ km.

Thus, the pickup ions detected by SLED should have their origin $5-6 \cdot 10^4$ km upstream of Mars. It can be stated that only a small fraction ($\sim 5 \cdot 10^{-5}$ O/cm^3) of Ip's (1990) extrapolated O-density ($\sim 10^{-1}$ O/cm^3) was detected by SLED as comprising energetic pickup ions.

It is noted that, during periods with 3-axis stabilisation of Phobos-2, pickup ions also appeared to be present but their identification is more difficult because SLED monitored only a limited part of space (55° ± 20° west of the S/C-sun line).

Pickup ions should have a north-south (south-north) anisotropy when the interplanetary magnetic field is directed along the $+y$ $(-y)$ axis and an eastwest (west-east) anisotropy when the magnetic field is directed northward (southward) from the ecliptic plane (Luhmann and Schwingenschuh, 1990). However, the measurements presented in Figs. 2, 3 and 4 do not allow the identification of anisotropies, since the aperture of SLED looks mainly in the sunward hemisphere.

Conclusions

1) Pickup ions, most likely constituting O^+ and O_2^+ ions of $E > 55$ keV, were observed in channels 1 and 2, especially during periods when Phobos-2 was spin-stabilised and the solar wind speed was > 500 km/s. They could be recognised above the background of solar particle events.
2) During 3-axis stabilisation, pickup ions can also appear but their identification in the data is difficult.
3) No further acceleration process for the pickup ions could be identified. The observed particle energies can be explained by the pickup process as discussed above.

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References

Afonin, V., S. McKenna-Lawlor, K. Gringauz, K. Kecskemety, E. Keppler, E. Kirsch, A. Richter, D. O'Sullivan, A. Somogyi, A. Thompson, A. Varga, and M. Witte, Energetic ions in the close environment of Mars and particle shadowing by the planet, *Nature*, **341**, 616–618, 1989.

Afonin, V. V., S. M. P. McKenna-Lawlor, G. Erdös, K. I. Gringauz, E. Keppler, K. Kecskemety, E. Kirsch, R. G. Marsden, A. K. Richter, W. Riedler, K. Schwingenschuh, A. Somogyi, D. O'Sullivan, L. Szabo, A. Thompson, A. Varga, K.-P. Wenzel, M. Witte, Ye. Yeroshenko, and L. Zelenyi, Low energy charged particles in near Martian space from the SLED and LET experiment aboard the Phobos 2 spacecraft, *Planet. Space Sci.*, **39**, 153–166, 1991.

Hynds, R. J., S. W. H. Cowley, T. R. Sanderson, K. P. Wenzel, and J. J. van Rooijen, Observations of energetic ions from comet Giacobini-Zinner, *Science*, **232**, 361–365, 1986.

Ip, W. H., On a hot oxygen corona of Mars, *Icarus*, **76**, 135–145, 1988.

Ip, W. H., The fast atomic oxygen corona extent of Mars. *Geophys. Res. Lett.*, **17**, 2289–2292, 1990.

Ip, W. H., and M. Banaszkiewicz, On the Dust/Gas torus of Phobos and Deimos, *Geophys. Res. Lett.*, **17**, 857–860, 1990.

Keppler, E., A note on the complication of the Compton Getting effect for low energy charged particle measurements in interplanetary space, *Geophys. Res. Lett.*, **5**, 69–72, 1978.

Luhmann, J. G., and K. Schwingenschuh, A model of the energetic ion environment of Mars, *J. Geophys. Res.*, **95**, 939–945, 1990.

Luhmann, J. G., A model of the ion wake of Mars, *Geophys. Res. Lett.*, **17**, 869–872, 1990.

Lundin, R., A. Zakharov, R. Pellinen, H. Borg, B. Hultqsvist, N. Pissarenko, E. M. Dubinin, S. W. Barabash, I. Liede, and H. Koskinen, First measurements of the Ionospheric plasma escape from Mars, *Nature*, **341**, 609–612, 1989.

Lundin, R., A. Zakharov, R. Pellinen, S. W. Barabasj, H. Borg, E. M. Dubinin, B. Hultqvist, H. Koskinen, I. Liede, and N. Pisarenko, Aspera/Phobos measurements of the ion outflow from the Martian ionosphere, *Geophysical Res. Lett.*, **17**, 873–876, 1990.

McKenna-Lawlor, S., E. Kirsch, D. O'Sullivan, A. Thompson, and K.-P. Wenzel, Energetic ions in the environment of comet Halley, *Nature*, **321**, 347–349, 1986.

McKenna-Lawlor, S., V. V. Afonin, K. J. Gringauz, E. Keppler, E. Kirsch, A. Richter, M. Witte, D. O'Sullivan, A. Thompson, A. J. Somogyi, L. Szabo, and A. Varga, The low energy particle detector SLED (~ 30 keV $-$ 3.2 MeV) and its performance on the Phobos mission to Mars and its moons, *Nucl. Instr. and Methods A*, **290**, 217–222, 1990.

Mihalov, J. D., and A. Barnes, Evidence for the acceleration of ionospheric O^+ in the magnetosheath of Venus, *Geophys. Res. Lett.*, **8**, 1277–1280, 1981.

Riedler, W., D. Möhlmann, V. N. Oraevsky, K. Schwingenschuh, Ye. Yeroshenko, J. Rustenbach, Oe. Aydogar, G. Berghofer, H. Lichtenegger, M. Delva, G. Schelch, K. Pirsch, G. Fremuth, M. Steller, H. Arnold, T. Raditsch, U. Auster, K.-H. Fornacon, H. J. Schenk, H. Michaelis, U. Motschmann, T. Roatsch, K. Sauer, R. Schröter, J. Kurths, D. Lenners, J. Linthe, V. Kobzev, V. Styashkin, A. Achache, J. Slavin, J. G. Luhmann, and C. T. Russell, Magnetic fields near Mars: First results, *Nature*, **341**, 604–607, 1989.

Roatsch, T., U. Auster, D. Möhlmann, and J. Rustenbach, Phobos 2 FGMM data during elliptical orbits, IKF Akademie der Wissenschaften der DDR, Preprint 4/89, 1989.

Rosenbauer, H., N. Shutte, I. Apathy, A. Galeev, K. Gringauz, H. Grünwaldt, P. Hemmerich, K. Jockers, P. Kiraly, G. Kotova, S. Livi, E. Marsch, A. Richter, W. Riedler, T. Remizov, R. Schwenn, K. Schwingenschuh, M. Steller, K. Szegö, M. Verigin, and M. Witte, Ions of martian origin and plasma sheet in the martian magnetosphere: Initial results of the TAUS experiment. *Nature*, **341**, 612–614, 1989.

Sagdeev, R. Z., and A. V. Zakharov, Brief history of the Phobos mission, *Nature*, **341**, 581–585, 1989.