Comparison of Jovian jets observed by Ulysses and Pioneer 10

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***Abstract*. Since the Pioneer 10/11 mission, Jupiter is known as a dominant and almost constant source of MeV electrons in the inner heliosphere. This picture has been confirmed later by the flybys of the Voyager 1/2 and Ulysses spacecraft. However, during the first and second Jupiter approach of the Ulysses spacecraft 1992 and 2003/04, respectively, short lived and highly anisotropic jets of MeV electrons were observed in the vicinity of the planet. In total, 35 events were reported for the 1992 period and 15 events for the distant approach in 2003/04. It was shown that these electrons are of Jovian origin that propagate along flux tubes connected to Jupiter's magnetosphere and carry energy spectra being modulated by Jupiter's rotation period (∼10h) into the interplanetary space. However, these modulation vanishes beyond 0.5 AU. In order to search for Jovian jets in other spacecraft data, we re-examined Pioneer 10 data for the period from 1973 to 1974. We found several events attributed to be Jovian jets. In this contribution we presentate a comparison of Ulysses and Pioneer 10 results and discuss implications for particle propagation in the IMF.**

***Keywords*: Jupiter, Jovian electrons, Jovian jets**

I. Introduction

Indication for the existence of a Jovian magnetosphere came from ground-based observations by radio-astronomers in the 1950's, who observed the emission of non-thermal radio waves at decimetric and decametric wavelengths [1]. In 1973 the existence of a large and dynamic Jovian magnetosphere with a complex plasma interior was confirmed by *in-situ* measurements of the Pioneer 10 spacecraft (see e.g. [8]). A remarkable observation of Pioneer 10 and its successor, Pioneer 11, was the identification of the Jovian magnetosphere as a dominant and almost constant point source of energetic electrons up to several MeV [10]. These electrons have been detected in the whole inner heliosphere and are a major contributor to the population of galactic cosmic rays in interplanetary space. It was shown that these Jovian electrons mainly propagate along the IMF (interplanetary magnetic field), so that an enhanced electron flux is detected every 13 months at Earth's orbit, i.e. when Earth and Jupiter are located on the same Parker field line and are interrupted by the ocurrence of Corotating Interaction Regions (see e.g. [4]), so that these energetic electrons are also called "quiet-time electrons".

However, during the first approach of Ulysses to Jupiter in 1991-1992, events of MeV electrons of very short duration have been detected in the vicinity of the planet [5]. These so-called Jovian jets are characterised by a sudden increase and decrease of flux, a short duration (several minutes up to a few hours), a strong anisotropy with respect to the local IMF and a spectrum being identical to the one observed in Jupiter's magnetosphere. Jovian jets only occur when the local IMF is aligned with the direction to Jupiter. Evidence for the Jovian origin is given by the fact that the 10 h periodicity of the energy spectrum inside the Jovian magnetosphere can be recovered up to 0.5 AU from the planet using a phasehistogram [5]. A total of 35 jets had been identified during the time period from day 356 in 1991 up to day 146 in 1992 within distances between 0.13 and 0.86 AU from the planet (cf. also Figure 1). In early 2004 Ulysses approached Jupiter again up to a distance of ∼0.8 AU. An analysis of the electron data from day 1 of 2003 to day 39 of 2005 lead to the identification of a total of 15 jet events within the range from 0.8 AU as far as 2.21 AU [9].

II. Instrumentation

For our analysis we use data of the Pioneer 10 and Ulysses spacecraft. The electron data were obtained from measurements of the University of Chicago instrument aboard Pioneer 10 and the Kiel Electron Telescope (KET) abord Ulysses. The KET is located perpendicular to the spin axis of the Ulysses spacecraft, which is pointing to Earth. The count rates of the E4 (2.5-7 MeV) channel are sectorised into eight segments of 45°, allowing to measure the anisotropy with respect to the spin plane. The same applies to the 3-6 MeV electron channel of the University of Chicago instrument (cf. Figure 2), which, however, is inclined 70° to the spin axis (cf. [3], [7]). The time resolution of the electron data of Pioneer 10 is 30 minutes.

III. Jovian jets observed by Pioneer 10

In order to look for Jovian jets in the Pioneer 10 data we scanned the time period from day 100 in 1973 (i.e. the first occurence of quiet-time electrons) to the end of 1974. The criteria for identifying an event as a Jovian jet are: (i) a significant increase and decrease in flux, (ii) a significant anisotropy, (iii) the local IMF has to be aligned to the direction to Jupiter. Applying these criteria to the data, we found 17 Jovian jets in the

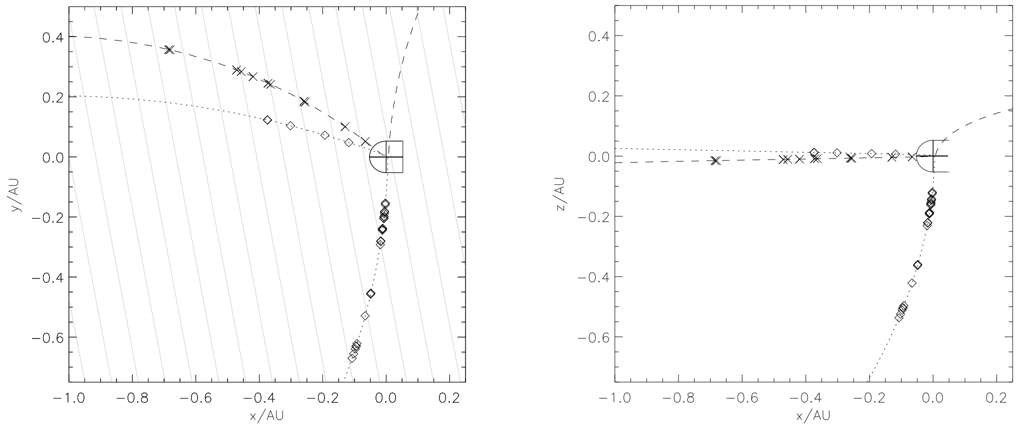

Fig. 1. Trajectories of Pioneer 10 (dashed line) and Ulysses (dotted line) during their Jupiter approaches in 1973 and 1992, respectively, in a Jupiter-centered coordinate system with x pointing away from the Sun. z is the rotation axis of the planet and y completes the right handed system. The Jovian jets we found in the Pioneer 10 data are marked by crosses ($\times$), those observed by Ulysses are indicated by diamonds ($\diamond$). The left panel shows the x-y-plane with additional Parker field lines in grey, while the right one shows the x-z-plane.

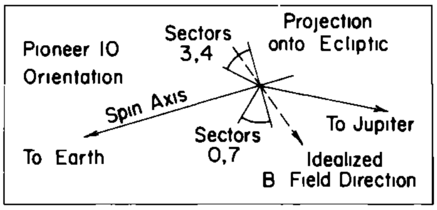

Fig. 2. Orientation of Pioneer 10 around day 245/1973 parallel to the ecliptic. Note the orientation of the acceptance cone with respect to Jupiter, taken from[3].

scanned Pioneer 10 data. We used roman numerals to label the events, if more than one jet belongs to the same events, additional letters are used. We found, however, several ambiguous electron events that can not clearly attributed to be Jovian jets and are therefore omitted in table I. Especially after the flyby at Jupiter, no Jovian jets could be identified unambiguously, mainly due to data gaps. Table I contains the following information: The jet ID, the start date of the jet (fractional day of year), the duration (hours, 30 minutes accuracy), the anisotropy with respect to the sector with maximum count rate and the distance to Jupiter in AU.

A. Spatial distribution and general properties of the jets

Fig. 1 shows the trajectories of Pioneer 10 and Ulysses during their Jupiter approaches in a Jupiter centered coordinate system. The Jovian jets we found in the Pioneer 10 data, are marked by crosses ($\times$), those observed by Ulysses are indicated by diamonds ($\diamond$). It is important to note that all Jovian jets listed in table I are found in time intervals, which [3] identified as times of enhanced flux anisotropies. However, their anisotropies were calculated from electrons fluxes averaged over several days, preventing an identification of short-term events we now identified as Jovian jets. To calculate jet anisotropies, we fitted the sector data to a Fourier analysis of the form

$$j(\Phi) = A_0(1 + A_1 \cos(\Phi - \Phi_1) + A_2 \cos[2(\Phi - \Phi_1)]),$$

TABLE I
JOVIAN JET EVENTS FOUND IN THE PIONEER 10 DATA

Jet ID	Date	$\Delta t(h)$	A_1 (%)	d (AU)
P10-Ia	190.90	2.5	26	0.79
P10-Ib	191.10	1.0	36	0.79
P10-Ic	191.55	4.5	56	0.79
P10-II	233.95	0.5	12	0.58
P10-III	236.80	1.5	25	0.55
P10-IV	245.14	3.5	90	0.51
P10-V	255.10	1.5	26	0.51
P10-VIa	257.20	1.5	23	0.46
P10-VIb	257.30	1.0	43	0.46
P10-VIIa	280.30	3.5	33	0.33
P10-VIIb	280.70	2.5	22	0.33
P10-VIIIa	281.40	2.0	89	0.33
P10-VIIIb	281.50	2.5	58	0.33
P10-IXa	309.80	2.5	30	0.18
P10-IXb	310.00	2.5	30	0.18
P10-Xa	325.05	1.5	35	0.09
P10-Xb	325.27	0.5	25	0.09

where A_1 and A_2 are the first-order and second-order anisotropy coefficients, respectively, and Φ_1 and Φ_2 are the corresponding symmetry axes. As mentioned above, no unambigious Jovian jet was found after the Jupiter encounter of Pioneer 10, i.e. when the spacecraft was in a position downstream of the planet. Considering the Pioneer 10 trajectory in Fig. 1 left, no Jovian jets are expected in this region due to the topology of the IMF, because a long-lasting flux tube angle with respect to the radial direction of $> 90°$ is required.

B. Jovian jets on day 281/1973

A typical jet structure is shown in Fig. 3. From top to bottom the plot shows selected pie diagrams of the anisotropy, the sector count rates of 3-6 MeV electrons (dark and light shadings indicate low and high count rates, respectively) and the total count rates in the 3-6 MeV electron channel. In the plotted time interval, two Jovian jets were found. The first jet (P10-VIIIa) occurs at 281.4 and lasts for $\sim$2 hours as can be seen by an increase in flux and a considerable anisotropy ($A_1 = 89\%$). After an intermission of 30 minutes,

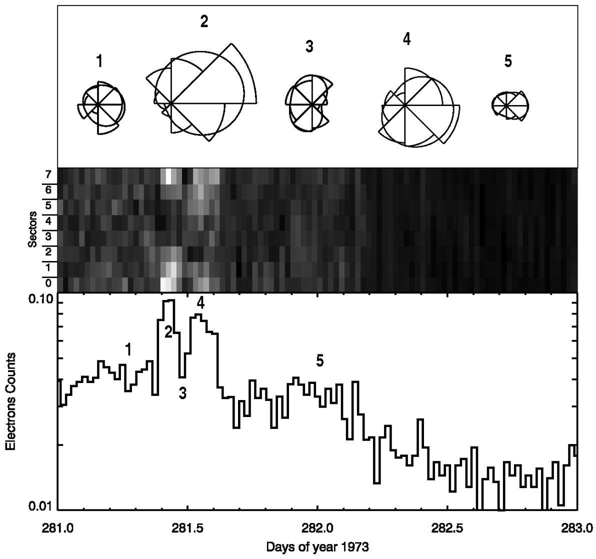

Fig. 3. The two jet events observed on day 281, 1973. A sudden increase of flux combined with a significant anisotropy is detected at 281.4 (P10-VIIIa). However, the flux decrease again for ~30 minutes to its background level and increases again with a maximum at 281.55 (P10-VIIIb). In the top panels the measured anisotropies are given by pie diagrams. The numbers correspond to the time of measurement.

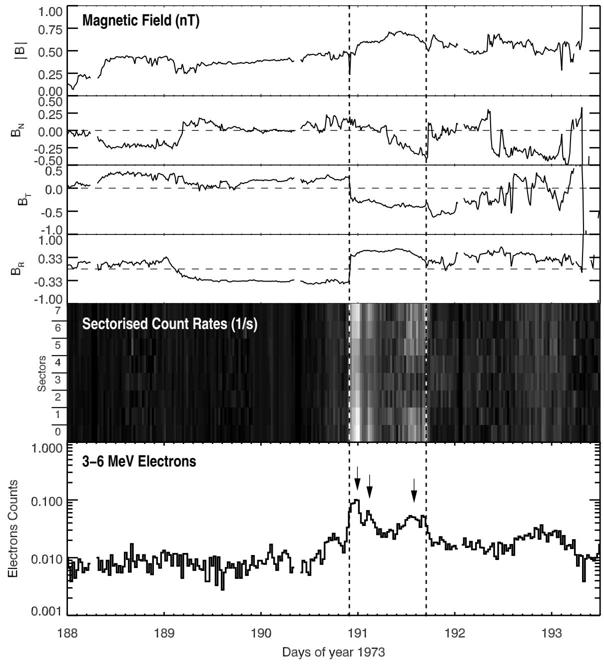

Fig. 4. Group of at least three Jovian jets observed by Pioneer 10 on day 190 of 1973 (P10-Ia,b,c, marked by ↓). Note the flux anisotropies and the jumps in the magnetic field components just before and after the occurence of the jets. See text for further details.

the second jet occurs, also indicated by an increase in flux and anisotropy ($A_1 = 58\%$). Confirming [3], Jovian electrons are expected to come predominantly from sectors 0 and 7 during the in-ecliptic trajectory of Pioneer 10 towards Jupiter. To illustrate the increase in flux and anisotropy during jet events, the pie diagrams in Fig. 3 show measured anisotropies for selected times as indicated by the corresponding numbers. When a jet occurs, an enhanced electron flux and a significant anisotropy is detected, while flux and anisotropy remain on a low level before and after the jet. Note that the sector of maximum intensity changes from sector 0 to 7, indicating a slight shift of the magnetic field line.

C. The jet structure on day 191/1973

Fig. 4 shows the time interval from day 188 to 193.5 in 1973. During this time, Pioneer 10 was approximately 0.8 AU upstream of Jupiter. From top to bottom, the plot shows the magnetic field strength and the magnetic field components in RTN-coordinates, the sector count rates of 3-6 MeV electrons to visualise the anisotropies. The last panel shows again the total count rates of 3-6 MeV electrons. Up to the end of day 190, the electron count rates remain on a fairly constant level of ~0.01 counts/s. This quiet-time behaviour is suddenly interrupted at 190.85, when a sudden increase of flux of about one order of magnitude is observed. This increase is accompanied by a strong chance in the magnetic field direction ($\Delta\vartheta = 154.9°$). The magnetic field changes its direction again significantly at 191.72 ($\Delta\vartheta = 65.1°$) and the flux decreases again. Within these two magnetic discontinuities, we identified three events as Jovian jets, indicated by arrows in Fig. 4. These flux increases are accompanied by clearly visible anisotropies ($A_1 = 26\%, 36\%,$ and 56%) with maxima at sectors 0 and 7. Note that event P10-Ic shows a fairly visible flux increase but a significant anisotropy. The magnetic discontinuities bounding the jets suggest the assumption that these events belong to a discrete magnetic flux tube (cf. [2]) connected to the Jovian magnetosphere, while the surrounding medium doesn't have a magnetic connection to Jupiter's magnetosphere.

D. Jovian jets and the 10h periodicity in the IMF

Shortly after the detection of Jupiter as a source of MeV electrons by Pioneer 10, it became evident that the 10h periodicity of charged particles can be recovered in the Jovian electron flux in the IMF as far away as 0.5 AU from the planet [3]. However, the authors noted that the conservation of the 10h periodicity at these distances can hardly be described by a simple diffusion equation. Fig. 5 shows the electron burst of day 243 to 246 in 1973 when Pioneer 10 was 0.5 AU away from the planet. The 10h periodicity [3] recovered in the time interval from day 217 to 246 is cleary visible in the interval bounded by lines in Fig. 5. Within the burst, we found the jet with the highest anisotropy (P10-IV, $A_1 = 90\%$) in the Pioneer 10 data, while the surrounding electron flux shows no remarkable anisotropy, but the 10h periodicity. [5] concluded from their analyses of Jovian jets observed by Ulysses that the 10h periodicity is mainly (or possibly even exclusively) found inside

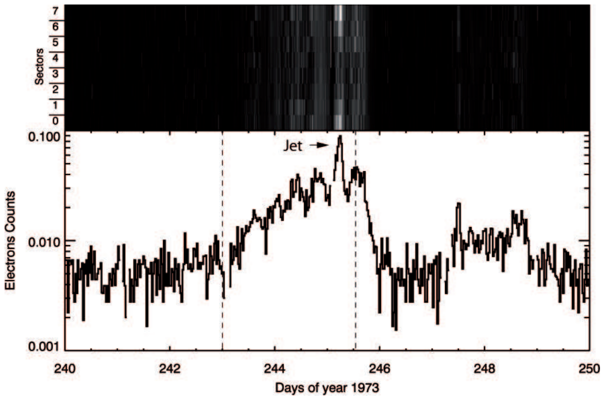

Fig. 5. Enhanced electron flux from day 243.5 to 245.5 in 1973, during which the 10h periodicity as well as a jet event are visible.

the jet events. However, the non-anisotropic electron flux carrying the 10h periodicity is related to the occurence of Jovian jets. From this we tentatively suggest that Jovian jets may play an important role for the occurence of the 10h periodicity within quiet-time electron events. The high anisotropies of Jovian jets suggest a nearly non-diffusive transport of particles and are therefore an appropriate mechanism to transport magnetospheric signatures to the IMF.

IV. Comparison of Ulysses and Pioneer 10 observations

The Ulysses trajectory (cf. Fig. 1) bends strongly southward after the Jupiter flyby, and most Jovian jets were detected in this part outside the plane of ecliptic. Only four events could be detected during the in-ecliptic approach in 1991 and early 1992, whereas we found 17 event in the Pioneer 10 data. A possible explanation for this difference could be geometry of the IMF as shown in Fig. 1 left, requiring less deviations from the nominal Parker spiral for the more sweeping Pioneer 10 trajectory. The anisotropies of the events we found in the Pioneer 10 data are less pronounced than those in the Ulysses data. The mean anisotropy of the 35 jets found by Ulysses during the first Jupiter approach is 69%, while that observed by Pioneer 10 is only 40%. The reasons for this may be the orientation of the Chicago Instrument with respect to the direction towards Jupiter (see Fig. 2), leading to a relatively poor pitch-angle coverage compared to Ulysses as well as our time resolution of 30 minutes, so time intervals outside of the jets could be included in the averaging.

V. Summary and Outlook

In this contribution we could show that Jovian jets as discovered during the first Ulysses flyby in 1992 occurred already during the Pioneer 10 flyby in 1973, but were not identified as such earlier due to the time averaging over several days [3]. Our re-examination of the Pioneer 10 data lead to the identification of 17 Jovian jet events which features being consistent with those found by Ulysses. While the lower anisotropies in the particle flux of the Pioneer 10 data may be attributed to instrumental effects, the higher occurence rate of jet events during the approach of the spacecraft towards Jupiter supports the model that the jets propagate along magnetic flux tubes (cf. [2]). These connect the spacecraft with the Jovian magnetosphere, a fact that usually requires a deviation of the magnetic field direction from the nominal Parker spiral. Further support is provided by jumps in the magnetic field occuring before and after some jets as well as the presence of the 10h periodicity of the Jovian magnetosphere within the jets, but probably not within the quiet-time electron events. The fact that the presence of the 10h periodicity is restricted to isolated events is consistent with observations e.g. by [6] that favour magnetic reconnection at the magnetopause as the main process leading to the generation of Jovian jets. The next steps will, thus, consist of a more detailled study of the origin and acceleration of the jets at the Jovian magnetosphere and the numerical modelling of the propagation of Jovian jet electrons along a magnetic flux tube.

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