Planetary and Space Science 58 (2010) 951–964

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

Three years of Ulysses dust data: 2005 to 2007

H. Krüger[a,b,*], V. Dikarev[c], B. Anweiler[b], S.F. Dermott[d], A.L. Graps[e], E. Grün[b,f], B.A. Gustafson[d], D.P. Hamilton[g], M.S. Hanner[h], M. Horányi[f], J. Kissel[a], D. Linkert[b], G. Linkert[b], I. Mann[i], J.A.M. McDonnell[j], G.E. Morfill[k], C. Polanskey[l], G. Schwehm[m], R. Srama[b,n]

[a] Max-Planck-Institut für Sonnensystemforschung, 37191 Katlenburg-Lindau, Germany
[b] Max-Planck-Institut für Kernphysik, 69029 Heidelberg, Germany
[c] Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany
[d] University of Florida, 211 SSRB, Campus, Gainesville, FL 32609, USA
[e] Department of Space Studies, Southwest Research Institute, 1050 Walnut Street Suite 300, Boulder, CO 80302, USA
[f] Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, CO 80309, USA
[g] University of Maryland, College Park, MD 20742-2421, USA
[h] Astronomy Department, 619 LGRT, University of Massachusetts, Amherst, MA 01003, USA
[i] School of Science and Engineering, Kindai University, Kowakae 3-4-1, Higashi-Osaka, Osaka 577-8502, Japan
[j] Planetary and Space Science Research Institute, The Open University, Milton Keynes MK7 6AA, UK
[k] Max-Planck-Institut für Extraterrestrische Physik, 85748 Garching, Germany
[l] Jet Propulsion Laboratory, Pasadena, CA 91109, USA
[m] ESAC, PO Box 78, 28691 Villanueva de la Cañada, Spain
[n] Universität Stuttgart, Institut für Raumfahrtsysteme, Pfaffenwaldring 31, 70569 Stuttgart, Germany

ARTICLE INFO

Article history:
Received 6 August 2009
Received in revised form
2 November 2009
Accepted 3 November 2009
Available online 12 November 2009

Keywords:
Interstellar dust
Interplanetary dust
Dust dynamics
Interstellar medium
Dust in-situ measurements

ABSTRACT

The Ulysses spacecraft has been orbiting the Sun on a highly inclined ellipse ($i = 79^\circ$, perihelion distance 1.3 AU, aphelion distance 5.4 AU) since it encountered Jupiter in February 1992. Since then it has made almost three revolutions about the Sun. Here we report on the final three years of data taken by the on-board dust detector. During this time, the dust detector recorded 609 dust impacts of particles with masses $10^{-16}\,\mathrm{g} \leqslant m \leqslant 10^{-7}\,\mathrm{g}$, bringing the mission total to 6719 dust data sets. The impact rate varied from a low value of 0.3 per day at high ecliptic latitudes to 1.5 per day in the inner solar system. The impact direction of the majority of impacts between 2005 and 2007 is compatible with particles of interstellar origin; the rest are most likely interplanetary particles. We compare the interstellar dust measurements from 2005/2006 with the data obtained during earlier periods (1993/1994) and (1999/2000) when Ulysses was traversing the same spatial region at southern ecliptic latitudes but the solar cycle was at a different phase. During these three intervals the impact rate of interstellar grains varied by more than a factor of two. Furthermore, in the two earlier periods the grain impact direction was in agreement with the flow direction of the interstellar helium while in 2005/2006 we observed a shift in the approach direction of the grains by approximately 30° away from the ecliptic plane. The reason for this shift remains unclear but may be connected with the configuration of the interplanetary magnetic field during solar maximum. We also find that the dust measurements are in agreement with the interplanetary flux model of Staubach et al. (1997) which was developed to fit a 5-year span of Ulysses data.

1. Introduction

Ulysses has been the only space mission so far that left the ecliptic plane and passed over the poles of the Sun. The spacecraft was launched in 1990 and was very successfully operated until 30 June 2009, although individual instruments had to be turned off to conserve power. Its orbital plane was almost perpendicular to the ecliptic plane (79° inclination) with an aphelion at Jupiter. This special orbit orientation allowed Ulysses to unambiguously detect interstellar dust grains entering the heliosphere because the spacecraft's orbital plane was almost perpendicular to the flow direction of the interstellar dust. Ulysses had a highly sensitive impact ionisation dust detector on board which measured impacts of micrometre and sub-micrometre dust grains. The detector was practically identical with the dust

E-mail address: krueger@mps.mpg.de (H. Krüger).

0032-0633/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.pss.2009.11.002

instrument which flew on board the Galileo spaceprobe. Both instruments were described in previous publications by Grün et al. (1992a, b, 1995c).

1.1. Summary of results from the Ulysses dust investigations

Comprehensive reviews of the scientific achievements of the Ulysses mission including results from the dust investigation were given by Balogh et al. (2001) and Grün et al. (2001). References to other works related to Ulysses and Galileo measurements on dust in the planetary system were also given by Grün et al. (1995a, b); Krüger et al. (1999a, b, 2001a, b, 2006b, a); Krüger and Grün (2009). Some mission highlights are also summarised in Table 1.

Various dust populations were investigated with the Ulysses and Galileo dust experiments in interplanetary space: the interplanetary dust complex including β-meteoroids (i.e. dust particles which leave the solar system on unbound orbits due to acceleration by radiation pressure), interstellar grains sweeping through the heliosphere, and dust stream particles expelled from the Jovian system by electromagnetic forces, to name only the most significant dust types detected with Ulysses which have been analysed so far. In the following, we summarise the most significant achievements of the Ulysses dust measurements.

Ulysses and Galileo dust measurements were used to study the 3-dimensional structure of the interplanetary dust complex and its relation to the underlying populations of parent bodies like asteroids and comets (Divine, 1993; Grün et al., 1997; Staubach et al., 1997). Studies of asteroidal dust released from the IRAS dust bands show that they are not efficient enough dust sources to maintain the observed interplanetary dust cloud (Mann et al., 1996). The state of the inner solar system dust cloud within approximately 1 AU from the Sun including dust destruction and ion formation processes in relation to so-called solar wind pickup ions detected by the Solar Wind Ion Composition Spectrometer (SWICS) onboard Ulysses was investigated (Mann et al., 2004; Mann and Czechowski, 2005). An improved physical model was developed for the interplanetary meteoroid environment (Dikarev et al., 2002, 2005) which uses long-term particle dynamics to define individual interplanetary dust populations. The Ulysses and Galileo in situ dust data are an important data set for the validation of this model. The properties of β-meteoroids were also studied with the Ulysses data set (Wehry and Mann, 1999; Wehry et al., 2004). Finally, the potential connection of cometary dust trails and enhancements of the interplanetary magnetic field as measured by Ulysses was discussed by Jones and Balogh (2003).

During its first flyby at Jupiter in 1992, the Ulysses dust instrument discovered burst-like intermittent streams of approximately 10 nm sized dust grains in interplanetary space (Grün et al., 1993) which had been emitted from the Jovian system (Hamilton and Burns, 1993; Horányi et al., 1993; Zook et al., 1996). This discovery was completely unexpected as no periodic phenomenon for tiny dust grains in interplanetary space was previously known. These grains strongly interacted with the interplanetary and the Jovian magnetic fields (Horányi et al., 1997; Grün et al., 1998) and the majority of them originated from Jupiter's moon Io (Graps et al., 2000). In February 2004 Ulysses had its second Jupiter flyby (at 0.8 AU distance from the planet) and again measured the Jovian dust streams (Krüger et al., 2006c; Flandes and Krüger, 2007).

Another important discovery made with Ulysses were interstellar dust particles sweeping through the heliosphere (Grün et al., 1993). The grains which originated from the very local interstellar environment of our solar system were identified by their impact direction and impact speed, the latter being compatible with particles moving on hyperbolic heliocentric trajectories (Grün et al., 1994). Their dynamics depends on the grain size and is strongly affected by the interaction with the interplanetary magnetic field and by solar radiation pressure (Landgraf et al., 1999; Landgraf, 2000; Mann and Kimura, 2000; Czechowski and Mann, 2003b, 2003a; Landgraf et al., 2003). As a result, the size distribution and fluxes of grains measured inside the heliosphere are strongly modified. Studies of the dust impacts detected with both Ulysses and Galileo showed that the intrinsic size distribution of interstellar grains in the local interstellar environment of our solar system extends to grain sizes larger than those detectable by spectroscopic observations of long sight-lines to stars, enabling information of intervening dust characteristics to be obtained (Frisch et al., 1999; Frisch and Slavin, 2003; Landgraf et al., 2000; Grün and Landgraf, 2000). Observations of radar meteors entering the Earth's atmosphere at high speeds also indicate the existence of even larger interstellar grains (Taylor et al., 1996; Baggaley and Neslušan, 2002).

The Ulysses and Galileo interstellar dust measurements showed that the dust-to-gas mass ratio in the local interstellar cloud is higher than the standard interstellar value derived from cosmic abundances (Landgraf, 1998; Frisch et al., 1999). This implied the existence of inhomogeneities in the diffuse interstellar medium on relatively small length scales. In 2005/2006 the Ulysses measurements showed a 30° shift in the impact direction of interstellar grains with respect to the interstellar helium flow (Krüger et al., 2007). The reason for this shift is presently unclear.

Finally, it turned out that the dust sensor side walls have a similar sensitivity to dust impacts as the detector target itself (Altobelli et al., 2004; Willis et al., 2005). This shows that earlier

Table 1
Summary of Ulysses data papers, significant mission events and dust detector switch-off times.

Time interval	Significant mission events	Dust detector off	Paper number
1990–1992	Ulysses launch (6 October 1990), Jupiter flyby (8 February 1992, distance 6.3 R_J)	Before 27 October 1990, 14 June 1991–18 June 1991	III (Grün et al., 1995a)
1993–1995	Maximum southern latitude -79° (3 October 1994), Perihelion (12 March 1995), Maximum northern latitude 79° (19 August 1995)	8 August 1993–11 August 1993, 27 November 1993–28 November 1993, 10 October 1994–11 October 1994, 10 December 1995	V (Krüger et al., 1999b)
1996–1999	Aphelion (20 April 1998)	17 August 1996–18 August 1996, 1 April 1997–2 April 1997, 15 February 1999–16 February 1999	VII (Krüger et al., 2001b)
2000–2004	Maximum southern latitude -80° (27 November 2000), Perihelion (23 May 2001), maximum northern latitude 80° (13 October 2001), Jupiter flyby (4 February 2004, distance 0.8 AU), Aphelion (30 June 2004)	26 March 2002–8 April 2002, 1 December 2002–3 June 2003, 28 June 2003–22 August 2003, 30 November 2003–2 December 2003	IX (Krüger et al., 2006a)
2005–2007	Maximum southern latitude -80° (7 February 2007), Perihelion (18 August 2007)	28 September 2006—-9 March 2007, 2 April 2007—-30 April 2007, After 30 November 2007	XI (this paper)

Jupiter radius $R_J = 71\,492$ km.