2.4 Ulysses

Introduction

Launched in 1990, Ulysses is an exploratory mission conducted jointly by ESA and NASA, with the primary objective of studying the interplanetary medium and solar wind as a function of heliographic latitude. There is good reason to believe that the conditions found in the narrow band of heliographic latitudes sampled by spacecraft confined to the ecliptic plane are not representative of the inner heliosphere as a whole, yet attempts to understand the basic physical processes occurring within this environment have so far been based essentially on observations made in the ecliptic plane. Ulysses has, for the first time, permitted measurements to be made in situ away from the plane of the ecliptic and over the poles of the Sun. Its unique trajectory, shown in Figure 2.4.1, has taken the spacecraft into the uncharted third dimension of the heliosphere.

The European contribution to the Ulysses programme consists of the provision and operation of the spacecraft and about half of the experiments. NASA provided the launch aboard the Space Shuttle *Discovery* (together with the upper-stage motor) and the spacecraft power generator, and is responsible for the remaining experiments. NASA also supports the mission using its Deep Space Network (DSN).

As stated above, the primary goal of the Ulysses mission is to measure the particles and fields that populate the heliosphere in the previously unexplored region of space extending from the Sun's equator to the poles, that is, as a function of heliographic latitude. The broad range of phenomena being studied by Ulysses includes the solar wind, the heliospheric magnetic field, solar radio bursts and plasma waves, solar and interplanetary energetic particles, galactic cosmic rays, interstellar neutral gas, cosmic dust, and gamma-ray bursts. A summary of the nine instruments that make up the spacecraft payload is presented in Table 2.4.1.

While the main focus of the mission is clearly concerned with latitudinal variations, other investigations carried out by Ulysses have included detailed interplanetary-physics studies during the in-ecliptic Earth-Jupiter phase (October 1990-February 1992), and measurements in the jovian magnetosphere during the Jupiter encounter. The spacecraft and ground telecommunication systems have been

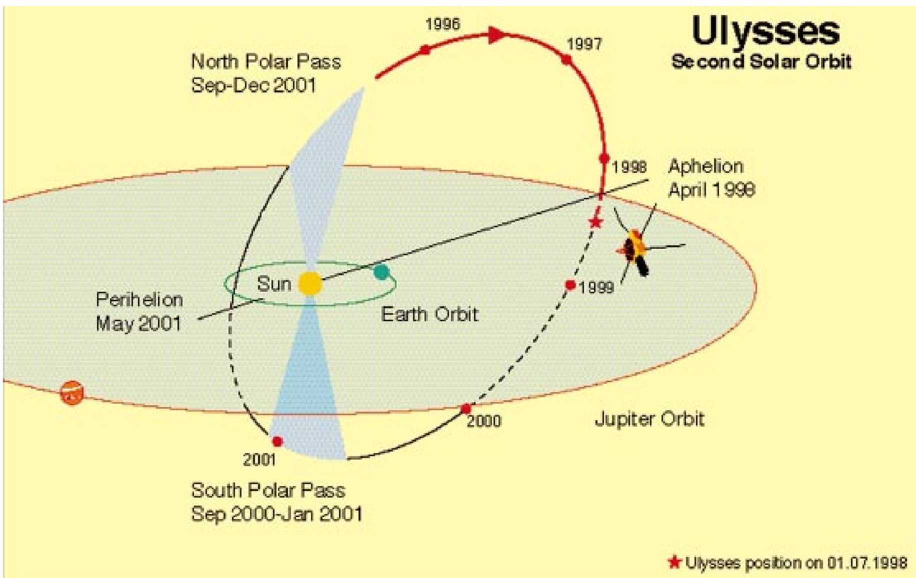


Figure 2.4.1. The Ulysses orbit, showing the second set of polar passes in 2000/2001. The spacecraft has just passed aphelion at a distance of 5.4 AU from the Sun.

Further information on Ulysses can be found at http://helio.estec.esa.nl/ulysses/

Table 2.4.1. The Ulysses scientific payload

Expt. Code	*Investigation*	*Scientific Acronym*	*Principal Investigator*	*Collaborating Institutes*
HED	Magnetic field	VHM/FGM	A. Balogh,Imperial College London (UK)	JPL (USA)
BAM	Solar wind plasma	SWOOPS	D.J. McComas, Los Alamos National Lab (USA)	Ames Research Center (USA); JPL (USA); HAO Boulder (USA) Univ of Boston (USA); MSFC (USA); MPAe Lindau (D)
GLG	Solar wind ion composition	SWICS	J. Geiss, ISSI (CH); G. Gloeckler, Univ of Maryland (USA)	Univ of New Hampshire (USA); GSFC (USA); TU Braunschweig (D); MPAe Lindau (D); Univ of Michigan (USA)
STO	Unified radio and plasma waves	URAP	R.J. MacDowall, GSFC (USA)	Obs de Paris Meudon (F); Univ of Minnesota (USA); CETP Velizy (F)
KEP	Energetic particles and interstellar neutral gas	EPAC/GAS	E. Keppler, MPAe Lindau (D)	Imperial College (UK); Swedish Inst Space Physics Kiruna & Umeå (S); Aerospace Corp (USA); Univ of Bonn (D); MPE Garching (D); Polish Acad Sciences (P)
LAN	Low-energy ions and electrons	HI-SCALE	L.J. Lanzerotti, Bell Laboratories (USA)	APL Laurel (USA); UC Berkeley (USA); Univ of Kansas (USA); Obs de Paris Meudon (F), Univ of Thrace (Gr); Univ of Birmingham (UK)
SIM	Cosmic rays and solar particles	COSPIN	R.B. McKibben, Univ of Chicago (USA)	Imperial College (UK); ESA Space Science Dept (NL); NRC Ottawa (Can); Univ of Kiel (D); CEN Saclay (F); Danish Space Res Inst (DK); NCR Milan (I); MPK Heidelberg (D); Univ of Maryland (USA); MPAe Lindau (D)
HUS	Solar X-ray and cosmic gamma-ray bursts	GRB	K. Hurley, UC Berkeley (USA) M. Sommer (retired), Samerberg (D)	CESR Toulouse (F); SRON Utrecht (NL); Obs de Paris Meudon (F); GSFC (USA)
GRU	Cosmic dust	DUST	E. Grün, MPK Heidelberg (D)	Univ of Canterbury (UK); ESA Space Science Dept (NL); MPE Garching (D); JSC (USA); Univ of Florida (USA)

used to conduct radio-science investigations into the structure of the corona and a search for gravitational waves.

In order to broaden the scope of the scientific work on Ulysses even further, a European Guest Investigator (GI) Programmme has been established. Nine investigations were selected in a peer review process at the beginning of 1997, and the GIs officially joined the Science Working Team at its meeting in April 1997. A complementary GI programme has been set up by NASA. Last, but not least, the Ulysses Science Team also includes the European Interdisciplinary Investigators who were selected together with the hardware teams. All of the above (radio-science, and European Guest and Interdisciplinary Investigations) are listed in Table 2.4.2.

Table 2.4.2. Ulysses radio-science, European Interdisciplinary and Guest Investigations

Investigation	*Principal/ Guest Investigator*
Coronal sounding (radio science)	M.K. Bird, Univ. Bonn (D)
Gravitational wave search (radio science)	B. Bertotti, Univ. Pavia (I)
Directional discontinuities (interdisciplinary)	M. Roth, IASB, Brussels (B)
Mass loss and ion composition (interdisciplinary)	G. Noci, Univ. Florence (I)
Guest investigations	
Investigation of tangential and rotational discontinuities in the solar wind at high latitude.	F. Neubauer, Univ. Cologne (D)
The structure and dynamics of interplanetary coronal mass ejections and microstreams observed by Ulysses.	P. Cargill, Blackett Laboratory, ICSTM (UK)
Kinetic modeling and data analysis of shocks, structures and flow in the 3-D heliosphere.	D. Burgess, Univ. London (UK)
A study of turbulent heliospheric processes.	T.S. Horbury, Blackett Laboratory, ICSTM (UK)
Investigation of Jovian and solar low-frequency radio emissions by using observations from the URAP experiment.	H.P. Ladreiter, SRI Graz (A)
Search for short- and long-term variability characteristics of quiet-time 0.1-100 MeV ion and electron fluxes.	P. Kiraly, KFKI Budapest (H)
Temporal characteristics, directivity and height distribution of solar X-ray/gamma-ray flares.	G. Trottet, Obs. de Paris (F)
Comparison between Ulysses measurements of solar wind proton flux and interplanetary Lyman-alpha measurements.	T. Summanen, FMI (SF)
Study of small-scale and large-scale structures of the heliospheric magnetic field.	G. Erdos, KFKI Budapest (H)

Spacecraft and mission status

Ulysses was launched by the Space Shuttle on 6 October 1990, using a combined IUS/PAM-S upper stage to inject the spacecraft into a direct Earth/Jupiter transfer orbit. A gravity-assist manoeuvre at Jupiter in February 1992 was used to place the spacecraft in its final Sun-centred out-of-ecliptic orbit, which has a perihelion distance of 1.3 AU and an aphelion of 5.4 AU. The orbital period is 6.2 years.

The mission is now in its eighth year, and all spacecraft systems and the nine sets of instruments that make up the scientific payload continue to function well. Spacecraft operations, conducted by the joint ESA-NASA Mission Operations Team at the Jet Propulsion Laboratory (JPL) in California, have proceeded in a highly efficient and productive way, ensuring the maximum possible data coverage (in excess of 95% throughout the mission). To obtain the latest information on Ulysses Mission Operations, see http://ulysses-ops.jpl.esa.int/~ulsfct/opsindex.htm

Details of the polar passes (defined to be the parts of the trajectory when the

Table 2.4.3. Key dates in the Ulysses mission

Events	*Date*
Launch	1990 10 06
Jupiter flyby	1992 02 08
start	1994 06 26
maximum latitude (80.2°, 2.3 AU)	1994 09 13
end	1994 11 05
1st Perihelion (1.34 AU)	1995 03 12
2nd Polar Pass (north)	
start	1995 06 19
maximum latitude (80.2°, 2.0 AU)	1995 07 31
end	1995 09 29
Start of Solar Maximum Mission	1995 10 01
Aphelion (5.40 AU)	1998 04 17
3rd Polar Pass (south)	
start	2000 09 08
maximum latitude (80.2°, 2.3 AU)	2000 11 27
end	2001 01 16
2nd Perihelion (1.34 AU)	2001 05 26
4th Polar Pass (north)	
start	2001 09 03
maximum latitude (80.2°, 2.0 AU)	2001 10 13
end	2001 12 12

spacecraft is above 70° heliographic latitude in either hemisphere) and other key mission milestones are presented in Table 2.4.3. The spacecraft reached aphelion in April 1998, thereby completing a full out-of-ecliptic orbit of the Sun. Moving slowly away from the equator in a southerly direction, Ulysses will arrive over the Sun's south polar regions for the second time in its exploratory journey at the end of 2000. By that time, solar activity will be near its maximum level, presenting Ulysses with a very different high-latitude environment from the one it encountered in 1994. Following the second 'fast latitude scan' from south to north, Ulysses will revisit the Sun's north pole in 2001.

Scientific highlights

In the 7.5 years since launch, Ulysses has provided an unprecedented perspective of the heliosphere around solar minimum. The Ulysses observations obtained so far have resolved a broad range of questions in the space sciences, due in large part to the unique orbit of the spacecraft. Figure 2.4.2 shows a sample of the Ulysses out-of-ecliptic data in the form of a polar diagram, with each trace representing actual measurements plotted versus the heliographic latitude of the spacecraft. Parameters shown are the solar wind speed (linear scale), the magnetic field polarity, and the fluxes of low-energy interplanetary and cosmic ray particles (logarithmic scales). For reference, the outer circle displays time starting in 1992.

Space limitations preclude a full discussion of the many fundamental results obtained by Ulysses during its investigation of the 3-dimensional heliosphere at solar minimum. First and foremost, as demonstrated in Figure 2.4.2, the mission has achieved its primary goal of providing an unprecedented set of measurements describing the behaviour of heliospheric particles and fields from the solar equator to

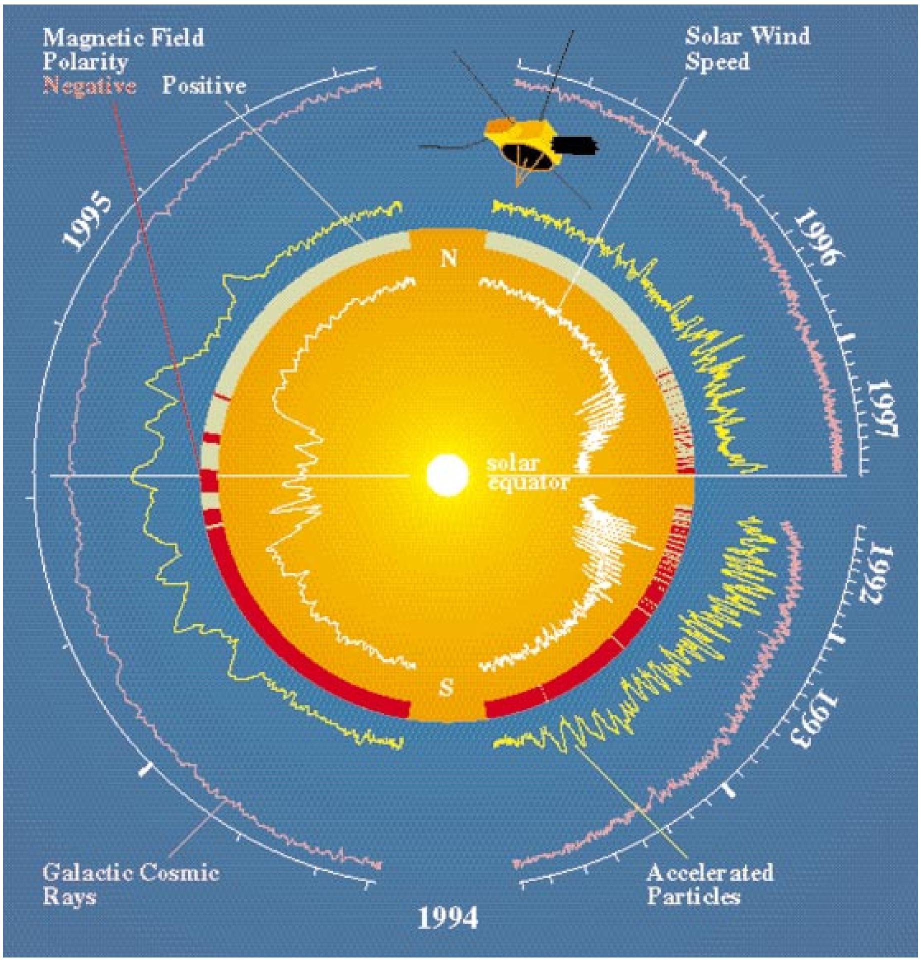


Figure 2.4.2. Polar plot showing actual measurements of solar wind speed (linear scale, range about 350-800 km/s), magnetic field (polarity), energetic particles and cosmic rays (logarithmic scales, with the cosmic ray trace offset with respect to the lower-energy particles) acquired by the Ulysses experiments. Particularly striking is the uniform fast (750 km/s) solar wind that fills a large fraction of the heliosphere above 30° latitude. Because of the elliptical nature of its orbit, Ulysses traversed the region represented in the left-hand side of the figure much more rapidly than that on the right. This accounts for the difference in appearance of the data traces in 1995 and 1996, for example. Time ticks are shown on the outer circle for reference.

the poles. Particularly striking in the Ulysses data is that the high-speed solar wind from the polar coronal holes is seen to expand to fill two-thirds of the heliosphere around solar minimum, even though the holes themselves occupy typically only 13% of the surface. Another feature clearly revealed by the polar plot is the relatively small increase in cosmic ray flux over the poles, a somewhat unexpected result. Although far from exhaustive, the following list represents some of the major accomplishments of Ulysses during its solar minimum mission:

— The characterisation of two distinct solar wind states, a fast high-latitude wind which only occasionally extends down to low latitudes, and a slow low-latitude wind centred about the heliospheric current sheet. These are separated by a sharp boundary extending from the corona down to the chromosphere.
— The discovery that the magnitude of the radial component of the heliospheric magnetic field does not increase towards the poles. The constancy of the radial field implies that the dipole-like configuration of the Sun's surface field is not maintained, and that, as a result, the polar solar wind undergoes significant non-radial expansion.
— The discovery that co-rotating solar wind stream structures with forward and

Figure 2.4.3. Cartoon showing new aspects of the heliosphere at solar minimum as revealed by Ulysses. Among the phenomena depicted are (a) fast solar wind filling the bulk of the heliosphere, separated from the near-equatorial slow wind by a relativley sharp boundary; (b) interstellar neutral gas, the source of pick-up ions which in turn form the anomalous cosmic ray component (ACR); (c) co-rotating interaction regions (CIR), giving rise to periodic variations in the intensity of energetic particles and cosmic rays up to high latitudes; (d) gamma-ray bursts; (e) the heliospheric magnetic field, with enhanced fluctuations at high latitudes scattering incoming cosmic rays, and field lines connecting high and low latitudes; (f) interstellar dust grains.

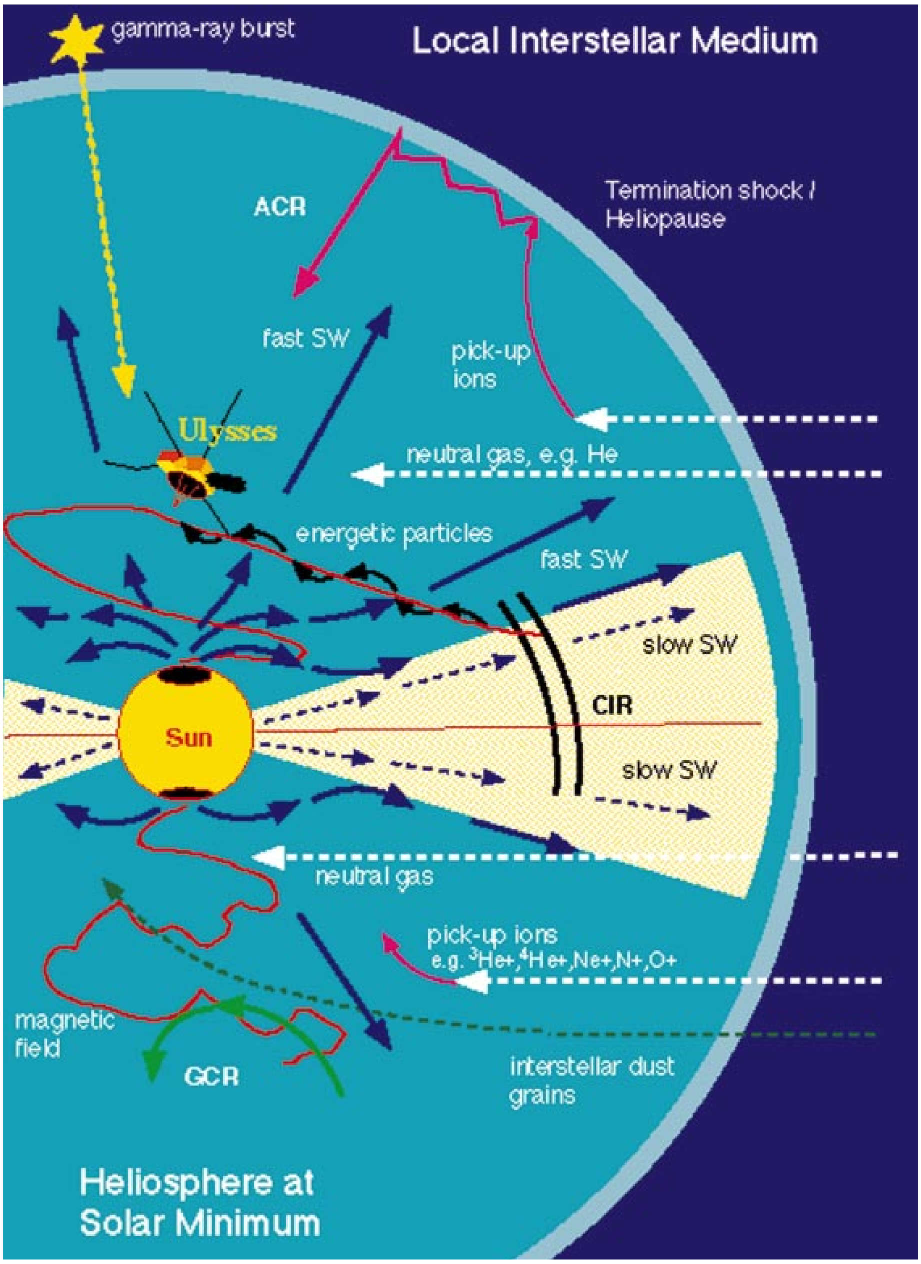
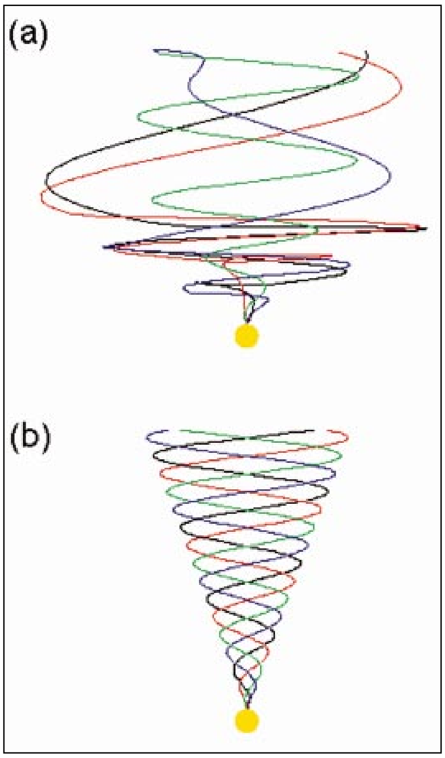


Figure 2.4.4. Ulysses' magnetic field measurements have caused theorists to revise their models of the heliospheric magnetic field. Shown here is high-latitude field configuration proposed by L. Fisk (a), compared with the traditional Archimedes spiral model (b) due originally to E. Parker.



reverse shock waves, well-studied at low latitudes and expected to be confined to those regions, produce effects extending to the highest latitudes explored by Ulysses. These effects include the recurrent modulation of galactic cosmic rays and injection of accelerated lower-energy particles into the polar regions, suggesting a revised global structure for the heliospheric magnetic field.

— The discovery that the influx of cosmic rays at high latitudes is smaller than predicted for this phase of the solar activity cycle.

— The determination of the flux and flow direction of interstellar dust grains passing through the solar system.

- The measurement of the flow parameters of interstellar helium, leading to an improved description of the motion of the solar system through the local interstellar cloud.
- The derivation of the density of interstellar atomic hydrogen and helium, leading to improved knowledge of the interaction of the local interstellar cloud with the heliosphere.
- The first-ever measurement of the interstellar $^3He/^4He$ ratio, the value of which suggests that the amount of dark matter produced in the Big Bang was greater than previously thought.
- The high-precision measurement of individual isotopes of cosmic ray C, N, O, Ne, Mg, Si, Fe and Ni, showing a source composition that is generally consistent with solar system matter. This suggests that cosmic rays are accelerated in the interstellar medium rather than being the products of explosive nucleosynthesis.
- The determination of the positions of gamma-ray bursts with unprecedented accuracy, including a contribution to the first plausible identification of an optical counterpart.

Figure 2.4.3 summarises these and other findings in schematic form.

In keeping with a mission of discovery like Ulysses, the output of the science teams working with Ulysses data has been, and continues to be, prolific. More than 750 papers have appeared in the scientific literature to date. An up-to-date bibliography can be found on the Ulysses web site at http://helio.estec.esa.nl/ulysses/

The future

The heliosphere is a dynamic structure that undergoes large variations in both large- and fine-scale structure over the period of an 11-year solar cycle. It is critical that observations are also obtained near solar maximum, and this will be accomplished during Ulysses' second orbit of the Sun, the so-called Ulysses Solar Maximum Mission. It is certain that new insights will be gained as we continue to observe the effects of increasing solar activity, changing coronal structure and, ultimately, the reversal of the solar magnetic polarity from the vantage point of Ulysses at high latitude in the coming solar maximum.

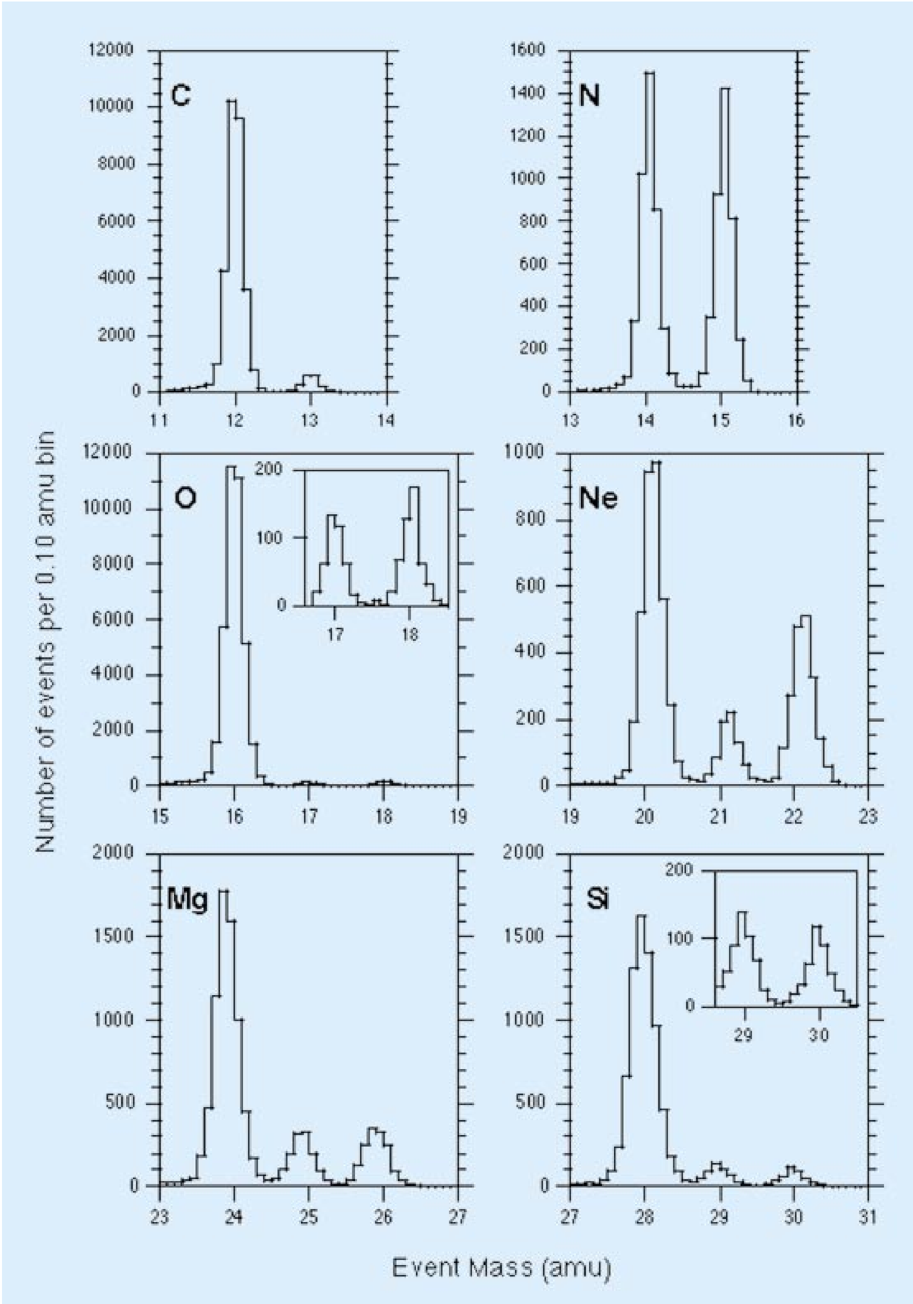
Many of the topics of the Ulysses Solar Maximum Mission can be addressed fully only when Ulysses revisits the polar regions in 2000-2001. Nonetheless, observations in the intervening period (1998-99) are critical for placing the later observations in context. Furthermore, we do not know when many of the processes related to the onset of solar maximum will begin to appear at the location of Ulysses.

An important aspect of the Ulysses Solar Maximum Mission will be the collaborations with many other spacecraft and ground-based projects that already characterise a significant part of the scientific work carried out using Ulysses data. In all such studies, the unique high-latitude perspective of Ulysses and its integrated instrument payload are invaluable assets.

Ulysses data archive

Data from the Ulysses investigations and flight project are being archived and made accessible to the public through two channels: the ESA Ulysses Data Archive located at ESTEC, and NASA's National Space Science Data Center (NSSDC). The ESA archive for Ulysses Data provides an on-line facility to browse and download selected measurements made by the scientific instruments onboard Ulysses. The user is able to view 26-day and 1-year summary plots of the main parameters measured, and to

Figure 2.4.5. Mass distributions of cosmic-ray C, N, O, Ne, Mg and Si isotopes measured by the COSPIN/HET experiment on Ulysses (courtesy J.J. Connell).



download ASCII data files and accompanying documentation for further analysis. Direct access to the plots, data files and documentation can be obtained by FTP to the ESA anonymous FTP server helio.estec.esa.nl (131.176.17.136), using ANONYMOUS as the account name and the user e-mail address as the password. All FTP access (with FTP directly or through a World Wide Web browser) to Ulysses data stored on the anonymous FTP server is logged. The ESA archive is accessible through the World Wide Web at URL http://helio.estec.esa.nl/ulysses/archive/