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Giant Planet Observations in NASA's Planetary Data System

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Abstract: While there have been far fewer missions to the outer Solar System than to the inner Solar System, spacecraft destined for the giant planets have conducted a wide range of fundamental investigations, returning data that continues to reshape our understanding of these complex systems, sometimes decades after the data were acquired. These data are preserved and accessible from national and international planetary science archives. For all NASA planetary missions and instruments the data are available from the science discipline nodes of the NASA Planetary Data System (PDS). Looking ahead, the PDS will be the primary repository for giant planets data from several upcoming missions and derived datasets, as well as supporting research conducted to aid in the interpretation of the remotely sensed giant planets data already archived in the PDS.

Keywords: giant planets; planetary atmospheres; planetary interiors; magnetospheres; data archiving; Jupiter; Saturn; Uranus; Neptune; Planetary Data System

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1. Introduction

Spacecraft exploration of the outer Solar System began with the arrival of Pioneer 10 at Jupiter in 1973, and continues to the present day with the Juno spacecraft in orbit around Jupiter. Unlike the more frequent orbiter and lander missions to destinations in closer proximity to Earth (e.g., the Moon or Mars), missions to the outer Solar System have been more scarce due to cost, power, and travel time constraints. Nevertheless, spacecraft destined for the giant planets have conducted a wide range of fundamental investigations, returning data that continues to reshape our understanding of these complex systems, sometimes decades after the data were acquired.

Early in the history of NASA's planetary missions, data archiving was somewhat unregulated: data were typically delivered from missions to Principal Investigators (PIs), who were individually responsible to clean, process, and document the data, and then to deposit them with the National Space Science Data Center Archive (NSSDCA) for permanent storage and public access. However, there was a realization in the late 1980s that careful stewardship of data was required to ensure both its accessibility and its usability for future generations of researchers. Not only were the data degrading (whether stored on analog media such as photographic film or scan tapes, or on digital media such as magnetic tapes), but subsequent attempts by others to use the data were failing despite conscientious efforts on the part of the PIs to provide sufficient documentation. It was recognized that these remote sensing (and also *in situ*) data represent a national treasure and a significant investment that must be preserved and maintained indefinitely.

NASA's Planetary Data System (PDS) was established with this aim in mind, following recommendations made by the Committee on Data Management and Computation (CODMAC) on behalf of the Space Science Board, National Academy of Sciences [1,2], with the PDS being one of a series of data systems recommended (the others covering other scientific disciplines such as Heliophysics and Astrophysics). CODMAC reviewed several archiving approaches and concluded that planetary datasets should reside at research institutions associated with the relevant scientific community, ensuring that scientists with direct experience in working with the data are closely involved in the archiving and curation process as well as the development of tools for data search, analysis, visualization, and planning observations.

To that end, the PDS is structured as a federated system of six Discipline Nodes (DNs) that provide unique expertise in various sub-disciplines of planetary science (Figure 1) [3]. Of these DNs, all but the Geosciences Node archive key remote sensing data sets related to the giant planets (specific examples are given in Section 2):

- The Atmospheres Node (ATM, https://pds-atmospheres.nmsu.edu, accessed on 30 October 2022) archives all non-imaging atmospheric data from planetary missions (excluding Earth observations), ground-based observations, and planetary analog, laboratory and field measurements.
- The Cartography and Imaging Sciences Node (IMG, https://pds-imaging.jpl.nasa.gov, accessed on 30 October 2022) archives digital image collections from planetary missions, and supports cartographic and geospatial data analysis.
- The Geosciences Node (GEO, https://pds-geosciences.wustl.edu, accessed on 30 October 2022) archives and distributes digital data related to the study of the surfaces and interiors of terrestrial planetary bodies.
- The Planetary Plasma Interactions Node (PPI, https://pds-ppi.igpp.ucla.edu, accessed on 30 October 2022) archives data related to the study of the interaction between the solar wind and planetary winds with planetary magnetospheres, ionospheres and surfaces.
- The Ring-Moon Systems Node (RMS, https://pds-rings.seti.org, accessed on 30 October 2022) archives data relevant to outer planetary systems, with a focus on individual data products within their original context. This includes remote sensing data (images, imaging spectrometer, and occultations) for systems beyond the asteroid belt (that is, Jupiter through Pluto). RMS also hosts the Radio Science Sub-Node (RSSN), which assists all of PDS with the ingestion and curation of radio science data, including gravity science and occultations.
- The Small Bodies Node (SBN, https://pds-smallbodies.astro.umd.edu, accessed on 30 October 2022) archives mission, ground-based, and laboratory data for objects generally described as comets, asteroids and interplanetary dust. This includes dwarf planets, objects in the Kuiper Belt and the Oort cloud, Centaurs, and small planetary satellites, as well as observations of the giant planets acquired en route to small body targets.

Data standards, i.e., the technical specifications used to describe data storage, sharing, and interpretation, are crucial for information transfer and interoperability. PDS standards ensure consistent description of planetary science data so that data providers, programmers, and end-users all know what to expect when creating and working with PDS files [4]. Historically, the PDS Requirements Review [2] laid out an ambitious design for preserving, cataloging, and distributing planetary datasets to users, all during a time that predated the widespread use of the internet. It consisted of a proposed three-stage rollout:

- PDS version 1.0: Focused on software infrastructure and catalog design (1990)
- PDS version 2.0: Basic operations in the central cataloging and distribution node, with two selected DNs being brought up to full operational status as test cases (1992–1993)
- PDS version 3.0: “Final” release with all DNs fully operational and user support in place (1994–1995)

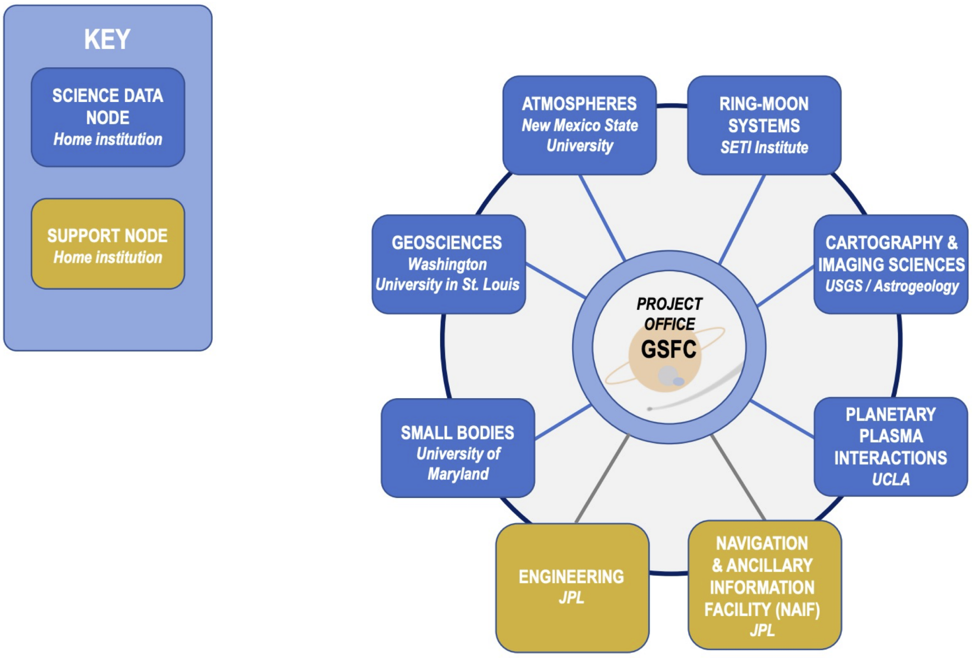


Figure 1. Organizational structure of the PDS. The Discipline Nodes are shown in blue boxes. The support nodes, shown in gold boxes, contain experts in areas that cover numerous missions. The Radio Science Subnode, currently at RMS, supports data providers and users with the specialized needs of radio science data.

By the mid-1990s, following feedback from users and data preparers, two major changes were implemented, resulting in what came to be known as PDS3 data standards (referring to v3.0 in the list above). First, major simplifications were made to the catalog file structures in order to streamline the process for users to locate and order datasets, and second, an attempt was made to rationalize and standardize the keywords used in labels by imposing some minimal metadata requirements.

Fifteen years following the introduction of PDS3, the process of developing and implementing new standards (PDS4) began, based on lessons learned during twenty years of archiving, current information systems concepts, and the capabilities inherent in the modern internet. PDS4 ensures more consistent standardization, better long-term preservation, and improved automation support [5]. Currently, all new datasets submitted to PDS comply with the PDS4 standards, and all existing PDS3 datasets are in the process of being migrated to PDS4. Further details of the history and data standards of the PDS are provided in Raugh and Hughes [6].

The release of the Memorandum from the President's Office of Science and Technology Policy entitled "Increasing Access to the Results of Federally Funded Scientific Research" in 2013 led to the development of the NASA Plan for Increasing Access to the Results of Scientific Research in 2014, the NASA Science Mission Directorate's Strategy for Data Management and Computing for Groundbreaking Science 2019–2024, and the NASA Science Mission Directorate's Policy Document SPD-41: Scientific Information Policy in 2021. Taken together, these documents codify the requirements surrounding the accessibility and preservation of digital data produced by NASA missions, instruments, and projects. The PDS has played a central role in serving as a publicly accessible and appropriate repository for archiving planetary data. The strength of the PDS lies in its long-term stability and the fact that all data are peer reviewed, both to ensure that they conform to the PDS standards and to confirm that they are well-documented and will be usable by future researchers. The PDS is an archive guided by the FAIR principles for scientific data management and stewardship, namely that the data should be findable, accessible, interoperable, and reusable.

After nearly five decades exploring the giant planets of our Solar System, the PDS is now responsible for the curation, preservation, and distribution of a wealth of remote sensing data on the outer planets. This includes data covering a wide range of wavelengths, instrumentation, acquisition modalities, targets, and physical processes. In this paper, we describe examples of such data in Section 2, discuss the modes through which these data can be accessed in Section 3, highlight anticipated future giant planets data and their application to both Solar System and exoplanetary science investigations in Section 4, and provide conclusions in Section 5.

2. Giant Planets Data in the PDS

Remote sensing data relevant to numerous science questions about the giant planets can be found across the PDS, illustrative of both the breadth and depth of the existing giant planets data. With the current PDS4 standards it should be immaterial where the data are actually located since they should be discoverable from any search within the PDS. However, the DNs still play an important and active role in working with and advising new and experienced data providers, data users, and tool developers who interact with data in the PDS.

In the following subsections we provide representative examples of giant planets data that are available from the PDS, organized by science area. **This is by no means an exhaustive list.** Rather, it is intended to showcase the aforementioned breadth of data and the physical processes they probe. Many instances of giant planet observations in the PDS archive were obtained when the planet was not encountered by the spacecraft, i.e., at distances where the planet is poorly resolved or unresolved by imaging instruments. We highlight here only datasets where the spacecraft was in the vicinity of the giant planet and conducted scientific observations during a flyby, or the planet was the subject of a prolonged orbiter mission. We also provide examples of Earth-based observations of the giant planets that are archived in the PDS.

2.1. Atmospheric Science

The most widely recognized attribute of the giant planets is their dynamic atmospheres, including the presence of latitudinally confined cloud bands, long-lasting vortices, discrete convective cloud features, auroral emissions, and evidence of bolide impacts. The PDS archives a broad range of observations that support investigations of these phenomena, including some with temporal coverage spanning several decades that enable studies of seasonal changes in the giant planet atmospheres and comparative studies between the four giant planets of our Solar System.

2.1.1. Atmospheric Composition

The chemical composition of gas giant atmospheres can yield critical insights into both their formation and evolution as well as dynamical processes taking place below the cloud tops. Abundance measurements for the most ubiquitous elements (helium, carbon, nitrogen, and sulfur) as compared to the corresponding solar values provide constraints on different planetary formation scenarios [7]. Global abundances and the spatial distribution of disequilibrium species (e.g., PH_3, CO) provide linkages between the atmospheric thermochemistry and the vertical convective motions, which also probes the heat balance of the deep atmosphere.

Several long-wave infrared (LWIR) spectrometers have flown on NASA missions to the outer planets, including the Infrared Interferometer Spectrometer and Radiometer (IRIS) instrument on Voyagers 1 and 2 and the Composite Infrared Spectrometer (CIRS) on Cassini. The flyby nature of the Voyager missions resulted in the same instruments being used to probe similar phenomena across all four of the giant planets, which can enable comparative studies. For example, data from the IRIS instruments were used to determine the helium abundance of Jupiter [8,9], Saturn [9,10], Uranus [11], and Neptune [12] (Figure 2). The 13 year duration of the Cassini mission enabled studies of seasonal variation in Saturn's atmospheric composition and chemistry using the CIRS data [13–15]. (Both the raw and calibrated CIRS data are archived in the PDS and are accessible from https://atmos.nmsu.edu/data_and_services/atmospheres_data/Cassini/inst-cirs.html and https://pds-rings.seti.org/cassini/cirs/index.html, both accessed on 30 October 2022).

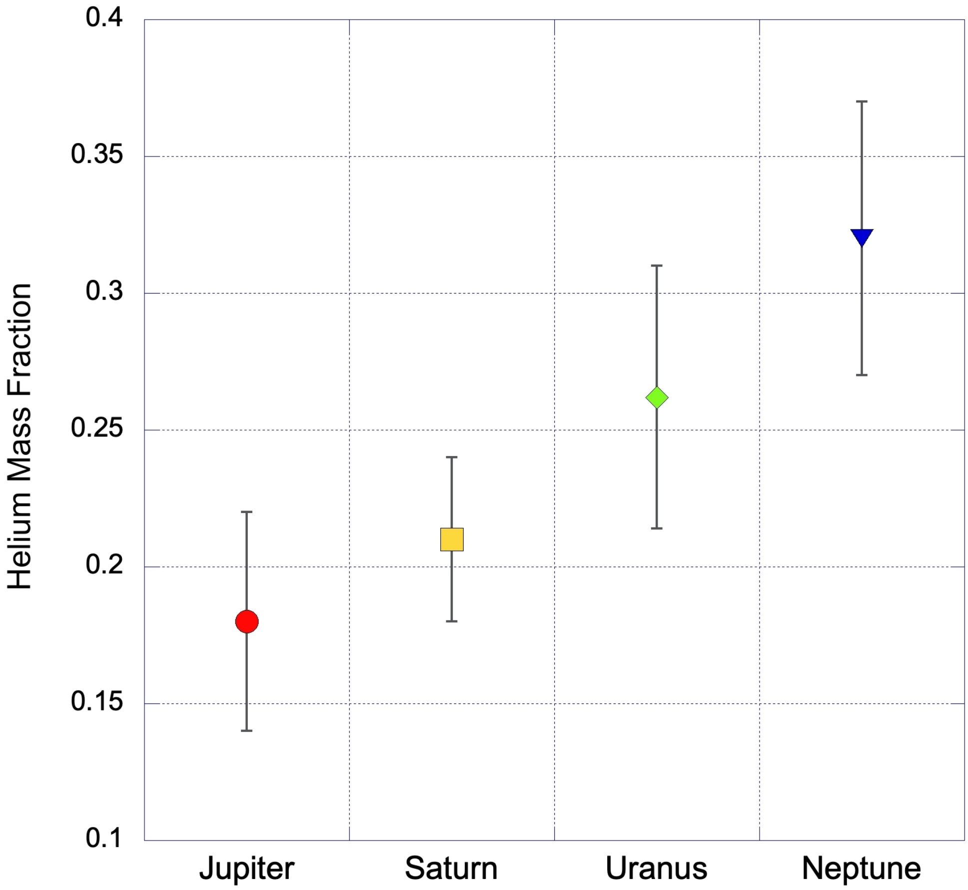


Figure 2. Helium abundances of Jupiter [9], Saturn [10], Uranus [11], and Neptune [12] derived from Voyager 1 and 2 IRIS observations.

2.1.2. Global Dynamics

Every mission to the giant planets was equipped with some form of an imaging camera (Table 1), resulting in a wealth of data in the PDS that can be used for studies of giant planet atmospheric dynamics. The Voyager flybys revealed the large-scale zonal structure of the atmospheric circulations of Jupiter [16,17], Saturn [18,19], Uranus [20], and Neptune [21], with the Galileo and Cassini orbiters revealing time-dependence and small-scale structure in the wind fields on Jupiter [22] and Saturn [23,24] , respectively. There were also valuable secondary imaging science opportunities during gravity assist flybys as conducted during Jupiter flybys by Cassini [25,26] and New Horizons [27].

The large-scale zonal and meridional wind speeds of the giant planets can be inferred through cloud-tracking techniques. This requires images with appropriate temporal spacing of ideally one to several hours: a time separation that is too small will not yield measurable motion, whereas a time separation that is too large increases the likelihood that the feature(s) being tracked will evolve and lose their fidelity. Cloud tracking techniques also are optimized when using images of high spatial resolution, which increases the number of features that can be tracked.

Table 1. Optical and near-infrared imagers used for remote sensing of Jupiter (J), Saturn (S), Uranus (U) and Neptune (N), and the Digital Object Identifiers (DOIs) for accessing the data. All links in this table were accessed on 30 October 2022.

Spacecraft	Instrument	Target	Access DOIs
Pioneer 10, 11	Imaging Photopolarimeter (IPP)	J, S	not available *
Voyager 1	Imaging Science Subsystem (ISS)	J S	https://doi.org/10.17189/1520214 https://doi.org/10.17189/1520304
Voyager 2	ISS	J S U N	https://doi.org/10.17189/1520214 https://doi.org/10.17189/1520304 https://doi.org/10.17189/1520365 https://doi.org/10.17189/1520412
Galileo	Solid State Imager (SSI) Near Infrared Mapping Spectrometer (NIMS)	J J	https://doi.org/10.17189/1520425 https://doi.org/10.17189/1520293
Cassini	Imaging Science Subsystem (ISS) Visual and Infrared Mapping Spectrometer (VIMS)	J S J, S	https://doi.org/10.17189/1520210 https://doi.org/10.17189/1520177 https://doi.org/10.17189/1520275
New Horizons	Long Range Reconnaissance Imager (LORRI) Multispectral Visible Imaging Camera (MVIC)	J	https://doi.org/10.26007/tcne-cm20 https://doi.org/10.26007/xmy5-zx84
Juno	JunoCam	J	https://doi.org/10.17189/1520191

* Pioneer 11 imaging data can be obtained from NSSDC, but not from the PDS.

2.1.3. Vortices

In addition to enabling the study of global dynamics of the giant planets, the imaging instruments described in Section 2.1.2 have also been used for detailed studies of discrete vortices. Long-lived storms like Jupiter's Great Red Spot have been characterized in terms of their chemistry and dynamics using observations from several instruments with data archived in the PDS [28,29]. In a more recent NASA mission, Juno's polar orbit has provided unprecedented access to the polar regions of Jupiter, and data from the JIRAM instrument (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO/jiram.html, accessed on 30 October 2022), as shown in Figure 3, revealed new insights into the formation, evolution, and vertical extent of polar vortex crystals.

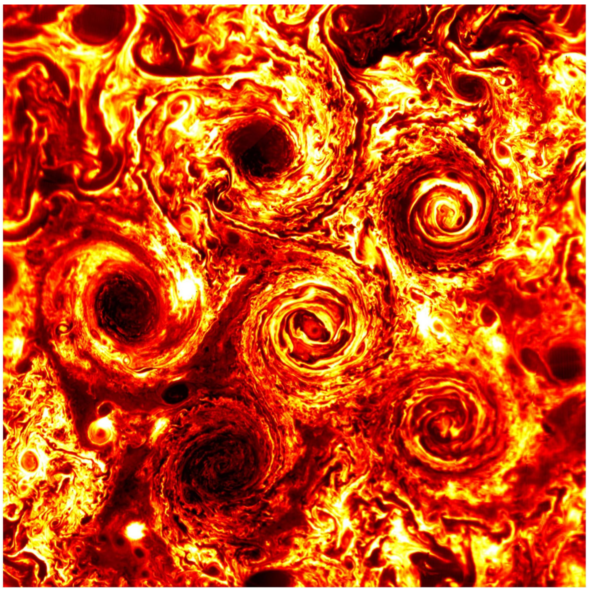


Figure 3. Six cyclones in Jupiter's south polar region as revealed by a Juno/JIRAM image taken on February 2, 2017, at a wavelength of roughly 5 microns. Image Credit: NASA/JPL-Caltech/SwRI/ASI/INAF/JIRAM (NASA PIA23556).

2.1.4. Vertical Profiles

The variation of atmospheric temperature as well as molecular mole fractions with depth (or pressure) can be inferred by radio or stellar occultations. In the former, the S or X band (or both) radio signals from the spacecraft are the source, and the reduction in signal as it passes from the spacecraft through a giant planet atmosphere to be received on Earth by the Deep Space Network can be analyzed to produce pressure-temperature profiles as well as vertical abundance profiles. For stellar occultations, a star is the source, and the dimming of starlight as measured by remote sensing instruments on board a spacecraft (or on Earth) can yield vertical profiles for atmospheric constituents [30], particularly when components of the occultation data are spectroscopic [31]. The radio science and UV and IR spectroscopic remote sensing instruments on board Voyager 1 and 2, Galileo, Cassini, New Horizons, and Juno have all been used to extract information about the behavior of the giant planet atmospheres with depth. A quick-look view of the types of data archived in the PDS for each giant planet is available through the Integrated Archive pages at the PDS Atmospheres Node. (For example, the Integrated Jupiter Data Archive page (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUPITER/matrices.html, accessed on 30 October 2022) provides a summary of the remote sensing instruments on board the spacecraft that flew by or orbited Jupiter.) Additionally, the RMS Node hosts 53 bundles of Earth-based, stellar occultations of the Uranian system (https://pds-rings.seti.org/pds4/bundles/uranus_occs_earthbased, accessed on 30 October 2022). Approximately half of these observations include atmospheric occultations by Uranus. They are presented as time series data, in units of counts-per-time, and are available for users who wish to further analyze them to generate vertical profiles of the Uranian atmosphere.

Other than occultations, the microwave observations from Juno's Microwave Radiometer (MWR) instrument are sensitive to deeper regions of the Jovian atmosphere (from 0.5 bar to hundreds of bars of pressure) than any previously flown giant planet remote sensing instrument. These data, which are available from the PDS Atmospheres Node (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO/microwave.html, accessed on 30 October 2022), are comprised of brightness temperatures in six different radiometric channels. The combination of data from MWR as well as instruments sensitive to Jupiter's upper troposphere (e.g., JIRAM or JunoCam) is a powerful approach for exploring the depths to which atmospheric phenomena such as waves or storms extend [32].

Atmospheric entry probes are the most direct way to gain information about the vertical structure of the giant planet atmospheres. To date, only the Galileo mission to Jupiter was equipped with a dedicated probe, which entered Jupiter's atmosphere on 7 December 1995. Key science results from the Galileo probe include the findings that Jupiter's zonal winds increased with depth and remained high (and constant) from 4 to 21 bars [33], the relatively cloud-free Jovian "hot spot" where the probe entered the atmosphere had an anomalously low water abundance [34], and the probe detected radio signals attributed to the existence of Jovian lightning [35]. Additionally, at Saturn, when Cassini approached and plunged into the atmosphere, Cassini Radio Science was actively following the spacecraft with multiple Deep Space Network (DSN) receivers until the signal was lost. These *in situ* data, the Galileo Probe and the End-of-Mission raw Cassini radio science data, are archived in the PDS Atmospheres Node (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/Galileo/galileo.html and https://atmos.nmsu.edu/data_and_services/atmospheres_data/Cassini/inst-rss.html, both accessed on 30 October 2022).

2.1.5. Upper Atmospheres and Aurora

Many of the spacecraft destined for the giant planets have been equipped with remote sensing instruments that enable the study of the neutral upper atmospheres, ionospheres, and auroral emissions. The ultraviolet spectrometers listed in Table 2 detected Ly_{α} emission from the giant planets, revealing the complex interactions between each planet's magnetic field and the solar wind and more local sources of charged particles. The Cassini Ultraviolet Imaging Spectrograph (UVIS) provided the most extensive dataset of a giant planet upper atmosphere to date. The UVIS observations of Saturn included solar and stellar occultations in the extreme ultraviolet (EUV) and far ultraviolet (FUV), dayglow spectral images, and images of the magnetosphere that show the vertical profile of neutral hydrogen escaping from Saturn's atmosphere [36]. As shown in Figure 4, the Grand Finale phase of the Cassini mission enabled views of Saturn's polar regions of unprecedented detail, revealing a complex structure of Saturn's aurora that relates to the quiet or disturbed nature of the nearby plasma [37].

In addition to the auroral processes probed by the ultraviolet instruments, the Jovian Infrared Auroral Mapper (JIRAM) instrument on board the Juno spacecraft is sensitive to the 3.3–3.6 µm emissions from H_3^+, which are used to characterize the morphology of the aurora and the conditions in the magnetosphere that lead to auroral emissions. The JIRAM nadir and limb observations of the H_3^+ emissions (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO/jiram.html, accessed on 30 October 2022) reveal complex morphology in Jupiter's auroral ovals and an anti-correlation between derived thermospheric temperatures and the H_3^+ density, reinforcing that H_3^+ emission is an atmospheric cooling mechanism [38].

Table 2. Ultraviolet spectrometers used for remote sensing of Jupiter (J), Saturn (S), Uranus (U) and Neptune (N), and the DOIs for accessing the data. All links in this table were accessed on 30 October 2022.

Spacecraft	Instrument	Target	Access DOIs
Voyager 1	Ultraviolet Spectrometer (UVS)	J S	https://doi.org/10.17189/4p9r-gc87 https://doi.org/10.17189/8ads-fr53
Voyager 2	UVS	J S U N	https://doi.org/10.17189/0w47-dq75 https://doi.org/10.17189/emh4-v313 https://doi.org/10.17189/fec9-4c64 https://doi.org/10.17189/2e17-9r73
Galileo	UVS	J	https://doi.org/10.17189/dv1z-cx79 https://doi.org/10.17189/8n8q-xf47
Cassini	Ultraviolet Imaging Spectrograph (UVIS)	J, S	https://doi.org/10.17189/4be3-xq57 https://doi.org/10.17189/zzgw-f046 https://doi.org/10.17189/kthj-r777
New Horizons	Alice Ultraviolet Imaging Spectrograph Linear Etalon Imaging Spectral Array (LEISA)	J J	https://doi.org/10.26007/qfvg-5k41 https://doi.org/10.26007/0cc7-4a49
Juno	Ultraviolet Spectrograph (UVS)	J	https://doi.org/10.17189/b29k-pv96 https://doi.org/10.17189/c32j-7r56

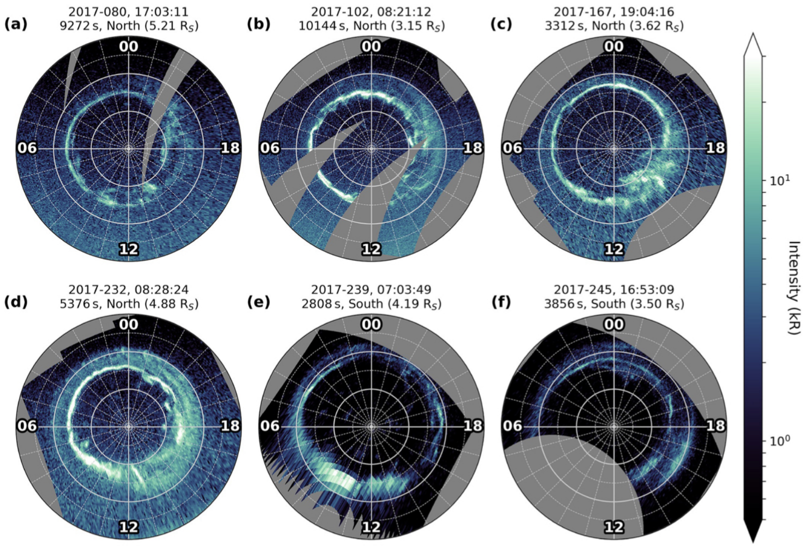


Figure 4. UVIS observations of Saturn's northern (**a**–**d**) and southern (**e**,**f**) auroral ovals during the Grand Finale phase of the Cassini mission. Figure reproduced from Bader et al. [37].

2.1.6. Impacts and Convective Outbursts

Impact events are ubiquitous throughout the Solar System, but they are challenging to observe without monitoring a target of interest night after night since they are signatures of a stochastic process. However, in the case of Comet Shoemaker-Levy 9 (SL9), whose 21 fragments impacted the Jovian atmosphere, observers had more than a year of advanced warning between the time the comet was discovered in March 1993 and the dates on which the fragments were predicted to impact Jupiter (July 1994). Numerous ground-based and space-based assets were used to observe the impacts, deriving information about the chemical composition of both the Jovian atmosphere and the comet fragments, the propagation of waves through the Jovian atmosphere, and the interaction of charged particles with both the magnetosphere and upper atmosphere of Jupiter. The spacecraft data from Galileo and Hubble Space Telescope are archived in the PDS Imaging Node and Atmospheres Node, respectively, and some ground-based observations of the SL9 impacts are also archived in the PDS Atmospheres Node (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/catalog.htm#Jupiter, accessed on 30 October 2022).

In addition to impacts, convective outbursts are another episodic phenomenon that can be used to probe vertical transport and moist convection in giant planet atmospheres. Although generally there is little indication *a priori* of when such a storm will take place, fortunately these events are often so energetic that their effects are visible for weeks or months after the initial outburst. Such was the case for the Saturn storm of 2010–2011, which was first detected in December 2010 and whose aftermath was detected through August 2011. The Cassini spacecraft was well positioned to acquire observations of the storm with its instrument suite (Figure 5), revealing new insights into Saturn's atmospheric structure, wind field, tropospheric cloud composition, stratospheric thermal structure and trace gas composition, ammonia vapor distribution, and associated lightning discharges [29]. These data are archived in the PDS Imaging (ISS and VIMS), Atmospheres (CIRS), RMS (ISS, VIMS and CIRS) and PPI (RPWS) nodes.

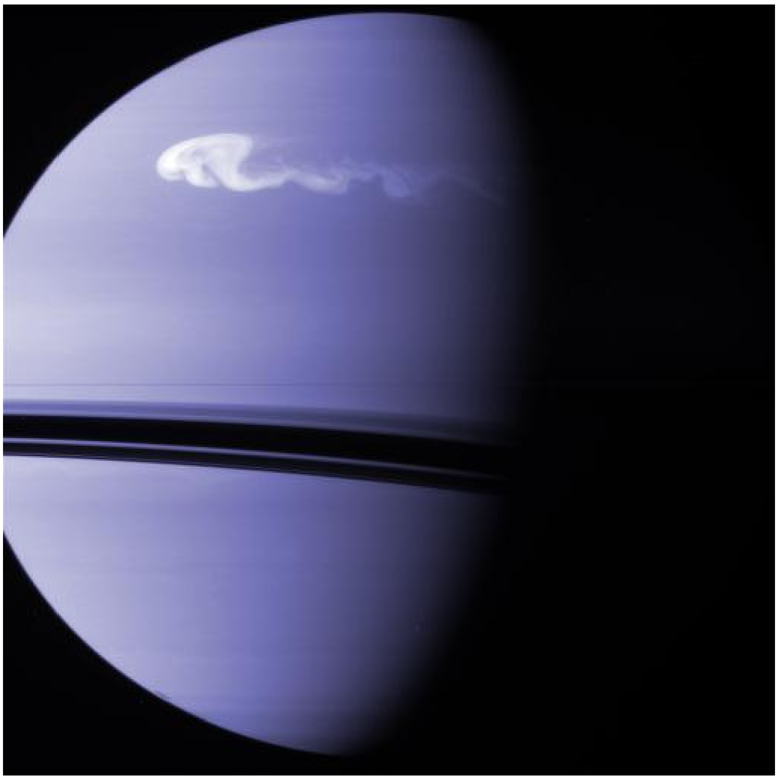


Figure 5. Cassini ISS image of the 2010 Saturn storm acquired on 24 December 2010. This image was downloaded from the PDS using the RMS OPUS tool (Section 3.1); the tint of this browse image is indicative of the wavelength range of the ISS filter through which the image was acquired (in this case, 429–492 nm).

2.1.7. Ground-Based Photometric Monitoring

Studies of seasonal changes in the atmospheres of the giant planets are by necessity long-term endeavors, given the orbital periods of the gas giants (approximately 12, 29, 84, and 164 years for Jupiter, Saturn, Uranus, and Neptune, respectively). There are few facilities that have been operating continuously and collecting data in a self-consistent manner that would enable long-term studies of the giant planets; the 21-inch telescope at Lowell Observatory is one such example. Disk-integrated albedos of Uranus and Neptune in the Strömgren b and y filters spanning the period 1972–2016 (Figure 6) [39] are archived in the PDS [40]. They reveal seasonal changes in the integrated brightness of the ice giant planets as well as short-term brightness changes that are likely due to the appearance and fading of large, discrete atmospheric features.

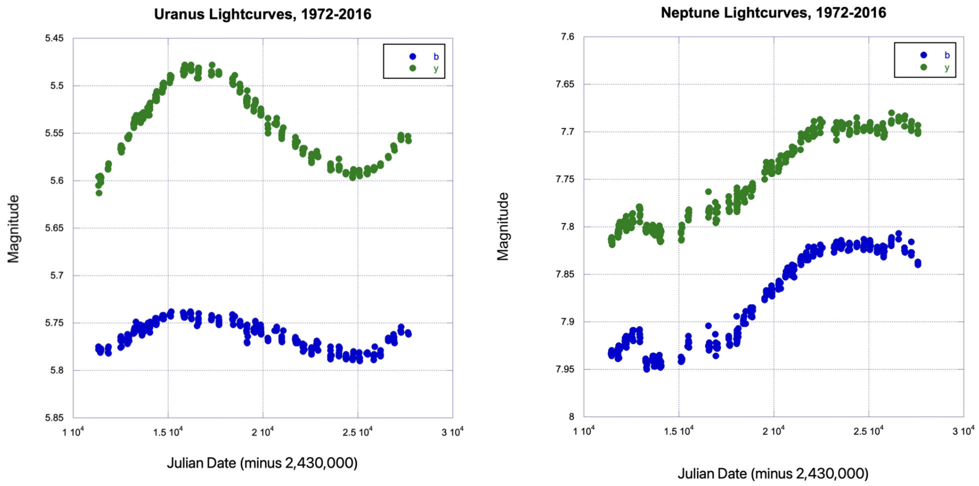


Figure 6. Disk integrated light curves of Uranus (**left**) and Neptune (**right**) in the Strömgren *b* (blue points) and *y* (green points) filters from 1972 to 2016.

2.2. Particles and Fields

Radio frequency emissions from Jupiter are very strong, at times even stronger than those of the Sun. Radio frequency observations at decametric wavelengths (∼22 MHz) were used to determine that Jupiter had an intrinsic magnetic field [41] before the first *in situ* observations by Pioneer 10. Other Jovian emissions include decametric radiation from synchrotron emissions of trapped electrons in Jovian radiation belts. The first spacecraft to make radio frequency observations were Voyager 1 and 2 in 1979. Both Voyager 1 and Voyager 2 carried a Planetary Radio Astronomy (PRA) experiment and a Plasma Wave Subsystem that measures electric and magnetic field waves in the range of Hz to 10 s of KHz. The radio and plasma wave investigations have probed the strong interaction between the moon Io and the upper atmosphere of Jupiter and have been used to determine the rotation rate of Jupiter. Plasma wave observations have been used to determine the electron density at Jupiter.

Since Voyager 1 and Voyager 2, the radio or plasma (or both) wave experiments have been flown on four subsequent missions to Jupiter. Table 3 gives the spacecraft and instruments, and the Digital Object Identifiers (DOIs) through which the data can be accessed directly from the PDS. The PDS is in the process of migrating all data holdings that were originally archived using the PDS3 metadata standard to the PDS4 standard, which provides a more modern archive structure and richer metadata. In cases where both PDS3 and PDS4 versions of the data are available, we list in Table 3 the access DOIs to the PDS4 data.

Figure 7 shows the radio spectra at the giant planets as well as that from Earth. As is the case for Jupiter, electromagnetic wave observations at Saturn have provided insight into the planetary rotation. However, at Saturn the period obtained called planetary period oscillations (PPO) is not the rotation period of the planet. The PPO period drifts over a time scale of years and is different for sources in the north and south (e.g., [42]). Its origin remains an area of intense study. Table 3 lists the radio astronomy and plasma wave data that are available from Saturn.

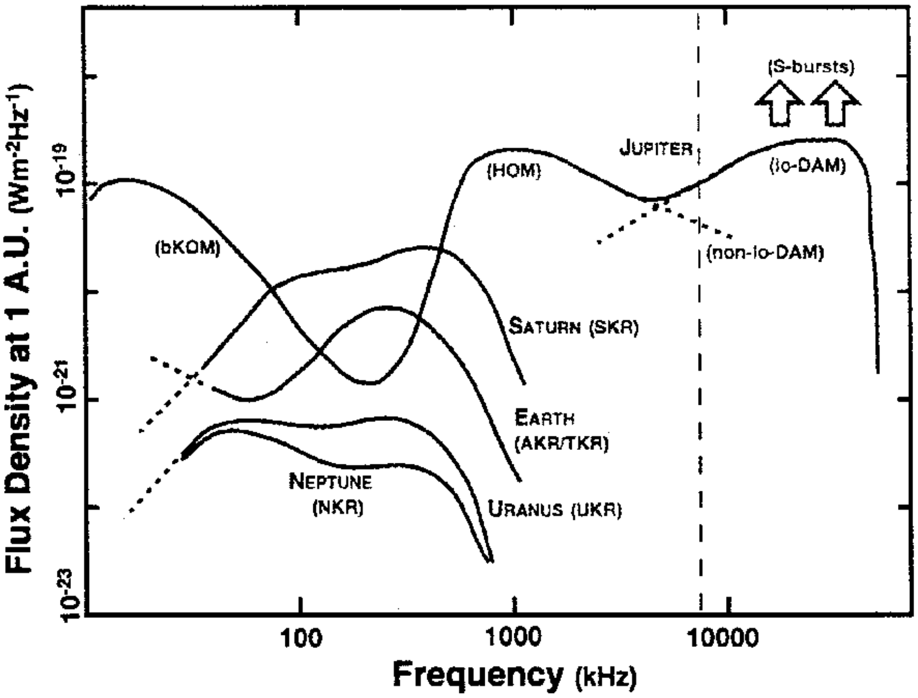


Figure 7. The radio spectra observed at Jupiter, Saturn, Earth, Uranus, and Neptune [43].

The Magnetospheric Imaging Instrument (MIMI) on Cassini provided a form of remote sensing of Saturn's magnetosphere not available for the other outer planets. The coexistence of trapped energetic ions and neutral gases in Saturn's magnetosphere allows the process of charge exchange to take place, in which an energetic particle takes an electron from a neutral particle, turning the ion into a neutral particle that is no longer magnetically trapped. The neutral particles can be imaged, providing a picture of the source energetic ion population, in a process called Energetic Neutral Atom (ENA) imaging. The Ion and Neutral Camera (INCA), was part of Cassini's MIMI package. The INCA camera data are available from the PDS (Table 3), including processed images and movies of the ENA that are included as browse files. In Figure 8, we show a sequence of four ENA images in the magnetosphere along with auroral EUV images in the ionosphere. The images show the injection of ions and the corresponding aurora. Note, the images of the ions map along magnetic field lines to Saturn's aurora and both rotate with Saturn.

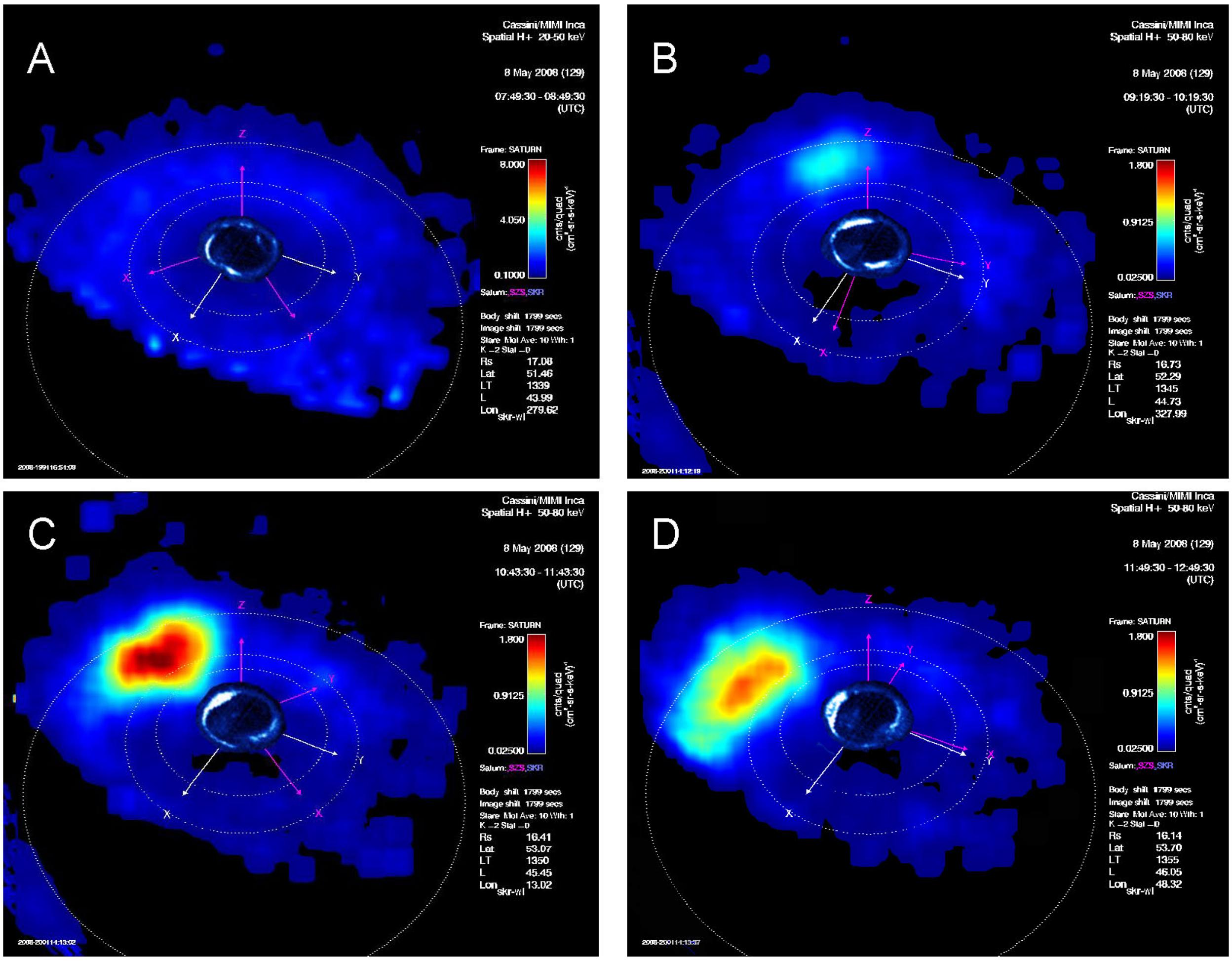


Figure 8. ENA images of Saturn's magnetospheric ions and auroral EUV emissions during an particle acceleration event on 8 May 2008 ((**A**) 0749–0849UT, (**B**) 0919–1019UT (**C**) 1043–1143UT, (**D**) 1141–1149UT). Currents along the magnetic field accelerate the particles producing the aurora. (Figure courtesy of Donald Mitchell, a movie of the ENA images can be found at https://doi.org/10.17189/1519607, accessed on 30 October 2022.)

Only Voyager 2 has visited Uranus and Neptune. Both the Planetary Radio Astronomy and the Plasma Wave Subsystem instruments returned data; these are also listed in Table 3.

Recently, all of the Voyager Plasma Wave Subsystem data have been made available in bundles covering the entire mission by using the PDS4 standard. The newly submitted PDS4 Voyager data are available in the NASA Common Data Format (CDF) format. PDS4 was designed to allow translation from the formats used in the archive to other formats. In space plasma research, the CDF format is widely used in research. PDS developed a version of CDF (called CDF-A) that adheres to PDS4 archival standards. A large number of research tools are available for data archived in CDF-A. The PPI Node is currently translating most of the PDS4 data in the archive into PDS4 documented CDF-A. Both the original PDS4 data and the translated data will be made available to users. Researchers wanting to use data translated into CDF-A can find the CDF-A standards documents and user guides at https://pds-ppi.igpp.ucla.edu/doc/index.jsp (accessed on 30 October 2022).

Table 3. Radio astronomy, plasma wave, and particle data for Jupiter (J), Saturn (S), Uranus (U) and Neptune (N) available in the PDS, and the DOIs for accessing the data. Several of the investigations listed have multiple data sets; in those cases, the range of sequential DOIs is given. All links in this table were accessed on 30 October 2022.

Spacecraft	Instrument	Target	Access DOIs
Voyager 1	Planetary Radio Astronomy Receiver (PRA)	J	https://doi.org/10.17189/1522972
		S	https://doi.org/10.17189/1522966
	Plasma Wave Spectrometer (PWS)	J	https://doi.org/10.17189/1519900 – https://doi.org/10.17189/1519905
		S	https://doi.org/10.17189/1519905 https://doi.org/10.17189/1519927 – https://doi.org/10.17189/1519928
		J, S	https://doi.org/10.17189/wp0z-1c51 – https://doi.org/10.17189/g5fy-rz59
Voyager 2	PRA	J	https://doi.org/10.17189/1519955
		S	https://doi.org/10.17189/1520011
		U	https://doi.org/10.17189/1520041 – https://doi.org/10.17189/1520043
		N	https://doi.org/10.17189/1519984 – https://doi.org/10.17189/1519986
	PWS	J	https://doi.org/10.17189/1519957 – https://doi.org/10.17189/1519962
		S	https://doi.org/10.17189/1519960 – https://doi.org/10.17189/1519962
		U	https://doi.org/10.17189/1519960 – https://doi.org/10.17189/1519962 https://doi.org/10.17189/1520044 – https://doi.org/10.17189/1520046
		N	https://doi.org/10.17189/1519987– https://doi.org/10.17189/1519989
		J,S,U,N	https://doi.org/10.17189/86sw-jn08 – https://doi.org/10.17189/bwn5-bs17
Ulysses	Unified Radio and Plasma Wave Experiment (URAP)	J	https://doi.org/10.17189/1519865 – https://doi.org/10.17189/1519873
Galileo	PWS	J	https://doi.org/10.17189/1519678 – https://doi.org/10.17189/1519684
Cassini	Radio and Plasma Wave Science (RPWS)	J	https://doi.org/10.17189/1519614 – https://doi.org/10.17189/1519617
		S	https://doi.org/10.17189/1519610 – https://doi.org/10.17189/1519617
	Magnetospheric Imaging Instrument (MIMI) Imaging Neutral Camera (INCA)	S	https://doi.org/10.17189/1519607
New Horizons	Pluto Energetic Particle Spectrometer Science Investigation (PEPSSI)	J	https://doi.org/10.26007/v0m7-pw47; https://doi.org/10.26007/hggb-f658
	Radio Science Experiment (REX)	J	https://doi.org/10.26007/61tf-4r89; https://doi.org/10.26007/f0cb-zn89
	Solar Wind Around Pluto (SWAP)	J	https://doi.org/10.26007/dfhh-kn63; https://doi.org/10.26007/q952-d227
	Student Dust Counter (SDC)	J	https://doi.org/10.26007/02b6-rm36; https://doi.org/10.26007/ke28-ke10
Juno	RPWS	J	https://doi.org/10.17189/1519708 – https://doi.org/10.17189/1520498
Radio Jove (Earth-based)	Radio Telescope	J	https://doi.org/10.17189/1520498 – https://doi.org/10.17189/1522500

In addition to the spacecraft observations of the giant planets, Jupiter can be readily observed from Earth's surface. In recent years, a worldwide program of continuous monitoring of Jovian radio waves has been maintained. In cooperation with the International Planetary Data Alliance (IPDA), PDS has archived and made available data from the Radio Jove project. The data are available in the archival version of the CDF-A format and in their native format used at radio observatories. The data from Radio Jove are also listed in Table 3. A unique aspect of the Radio Jove program is that it includes contributions from both professional and amateur observers. An inexpensive receiver that can detect the Jovian emissions is available through the NASA Radio Jove web site (https://radiojove.gsfc.nasa.gov/, accessed on 30 October 2022).

Planetary particles and fields data are of interest to scientists in both the astronomy and heliophysics communities. In addition to direct access from PPI, the data are being made available through the International Virtual Observatory Alliance's (IVOA) protocol (EPN-TAP) and the Heliophysics API (HAPI). These will enable users in those communities to stream the data using the protocol with which they are familiar. At this writing, all of the Voyager and Cassini data are available through EPN-TAP and the Voyager, Cassini and Galileo data are available through the HAPI server. In addition, PPI supports the TOPCAT (Tool for OPerations on Catalogs And Tables) display system for data using EPN-TAP and Autoplot for data accessed through HAPI.

2.3. Interiors

The deep atmospheres and interior structure of the giant planets can be probed through gravity measurements, whereby the returned radio signal from the spacecraft is used to quantify slight deviations in its orbit due to the gravitational influence of the planet on the spacecraft. The Doppler shifts of the signals from the radio science instruments on board Voyager 1 and 2, Cassini, and Juno were measured by the Deep Space Network to probe the gravity fields of the giant planets. For example, recent analyses of measurements made by the Juno Gravity instrument revealed new insights into the depth limits of Jupiter's zonal winds [44] and Jupiter's asymmetric gravity field [45]. The radio science data for the giant planets are archived in the PDS at the PPI Node (Voyager and Galileo), the Atmospheres Node (Cassini and Juno) and the Small Bodies Node (New Horizons). The Radio Science subnode, housed at the Ring-Moon Systems Node, serves all of the PDS and provides expertise on working with radio science data.

Additionally, certain waves in Saturn's rings have been used as records of processes originating in Saturn's interior, similar to the information provided by a terrestrial seismometer ([46] and references therein). The data facilitating this research is primarily the derived occultation profiles taken from Cassini VIMS (https://pds-rings.seti.org/viewmaster/volumes/COVIMS_8xxx, accessed on 30 October 2022) and RSS (https://pds-rings.seti.org/viewmaster/volumes/CORSS_8xxx, accessed on 30 October 2022).

3. Data Discoverability and Usability

Given the diversity of giant planets data in the PDS, examples of which are described in Section 2, accessing and making use of those data might seem like a task that requires advanced knowledge of data processing and visualization, file manipulation, or data engineering. Here we discuss various methods already implemented – some across the PDS and some at specific Discipline Nodes – to aid in giant planets data search and discovery.

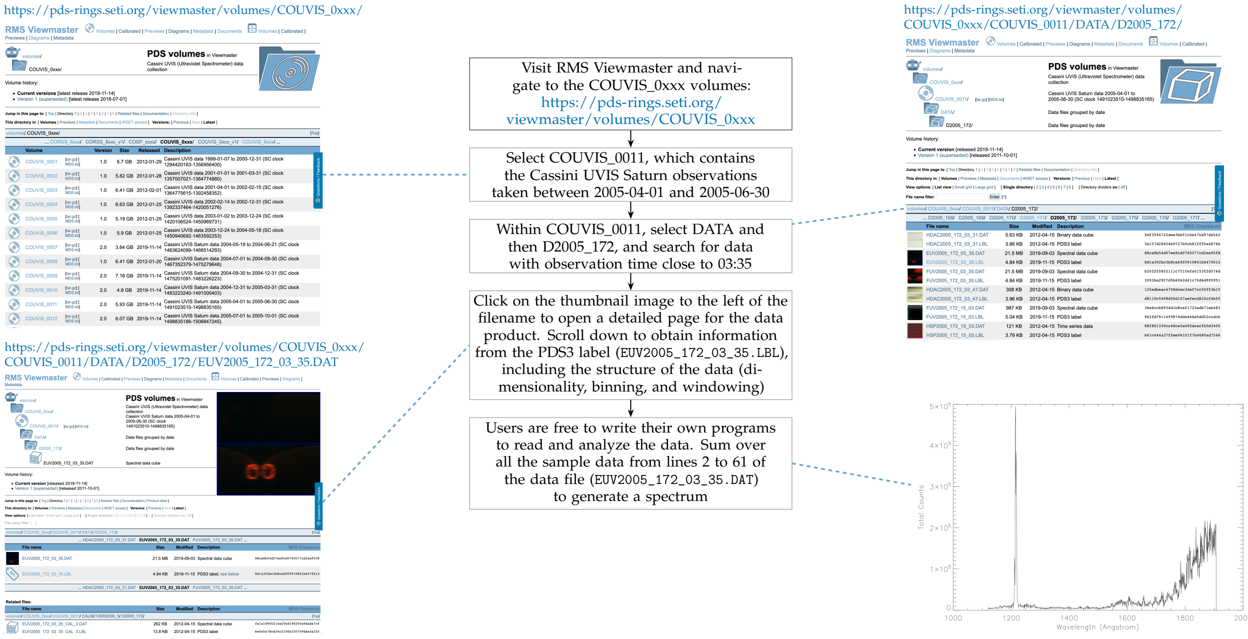
A new user to the PDS, or an experienced user who is interested in exploring the PDS holdings rather than conducting a focused search for something specific, should start at the PDS homepage (https://pds.nasa.gov, accessed on 30 October 2022). From there, the Data Search function enables users to search by Target (e.g., Uranus System) or Mission (e.g., Voyager). In each case the search returns links to (a) specific search tools – including those described in the following subsections – that are most appropriate for finding the data of interest, and (b) resource pages containing more information about the PDS holdings in the area of interest.

Experienced PDS users, or those who know more specifically what kind of giant planets data they are searching for, may wish to begin their search at the relevant DN. There users can make use of sophisticated tools developed by the DNs that enable searching on parameters such as observing geometry, positional information, or science theme. Examples of such tools are described in the following subsections.

3.1. OPUS and Viewmaster: Search and Browse the RMS Archive

An enhanced data browser is provided by Viewmaster (https://pds-rings.seti.org/viewmaster/volumes, accessed on 30 October 2022), which allows users to see every data volume in the RMS archive within an intuitively designed framework so that corresponding preview images, diagrams, indices, and documentation are listed in parallel to each data product, and related files can be found straightforwardly. The process of finding and using PDS data archived by the RMS Node is illustrated in Figure 9 by an example of how a user can generate a spectrum of Saturn's aurora.

Alongside Viewmaster, seamless cross-mission cross-instrument search for spacecraft and ground-based remote sensing observations is provided by the RMS Node's Outer Planet Unified Search (OPUS) tool (https://opus.pds-rings.seti.org, accessed on 30 October 2022). OPUS uses extensive metadata generated by the RMS Node using the most current SPICE kernels for enhanced search capabilities and provides preview images for an enhanced browsing experience, so users can easily filter down through the available holdings to reach the desired data products. Figure 10 illustrates how a user could search through OPUS to obtain the same data (and find additional metadata) used to plot the spectrum described in Figure 9. OPUS supports full geometric search of the giant planets for Voyager ISS, Cassini CIRS, ISS, UVIS, and VIMS, and New Horizons LORRI.



https://pds-rings.seti.org/viewmaster/volumes/COUVIS_0xxx/

https://pds-rings.seti.org/viewmaster/volumes/COUVIS_0xxx/COUVIS_0011/DATA/D2005_172/EUV2005_172_03_35.DAT

https://pds-rings.seti.org/viewmaster/volumes/COUVIS_0xxx/COUVIS_0011/DATA/D2005_172/

Visit RMS Viewmaster and navigate to the COUVIS_0xxx volumes: https://pds-rings.seti.org/viewmaster/volumes/COUVIS_0xxx

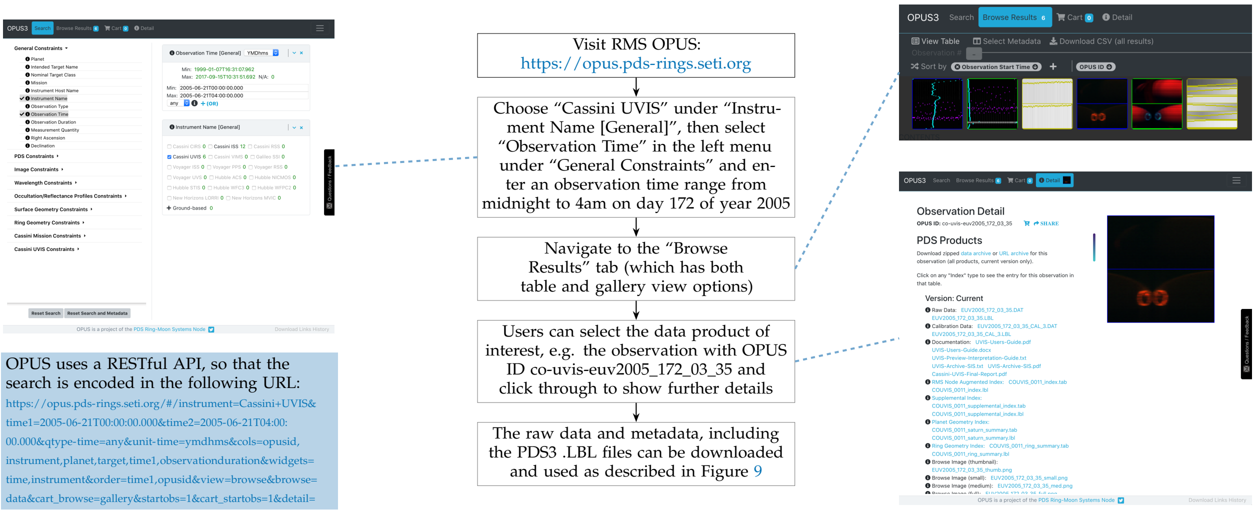
Select COUVIS_0011, which contains the Cassini UVIS Saturn observations taken between 2005-04-01 and 2005-06-30

Within COUVIS_0011, select DATA and then D2005_172, and search for data with observation time close to 03:35

Click on the thumbnail image to the left of the filename to open a detailed page for the data product. Scroll down to obtain information from the PDS3 label (`EUV2005_172_03_35.LBL`), including the structure of the data (dimensionality, binning, and windowing)

Users are free to write their own programs to read and analyze the data. Sum over all the sample data from lines 2 to 61 of the data file (`EUV2005_172_03_35.DAT`) to generate a spectrum

Figure 9. Step-by-step instructions on how to find and obtain UVIS data from the PDS via RMS Viewmaster for an observation of Saturn's aurora carried out around 03:35 on day 172 of year 2005. All links in this figure were accessed on 30 October 2022.



Visit RMS OPUS: https://opus.pds-rings.seti.org

Choose "Cassini UVIS" under "Instrument Name [General]", then select "Observation Time" in the left menu under "General Constraints" and enter an observation time range from midnight to 4am on day 172 of year 2005

Navigate to the "Browse Results" tab (which has both table and gallery view options)

Users can select the data product of interest, e.g. the observation with OPUS ID co-uvis-euv2005_172_03_35 and click through to show further details

The raw data and metadata, including the PDS3 .LBL files can be downloaded and used as described in Figure 9

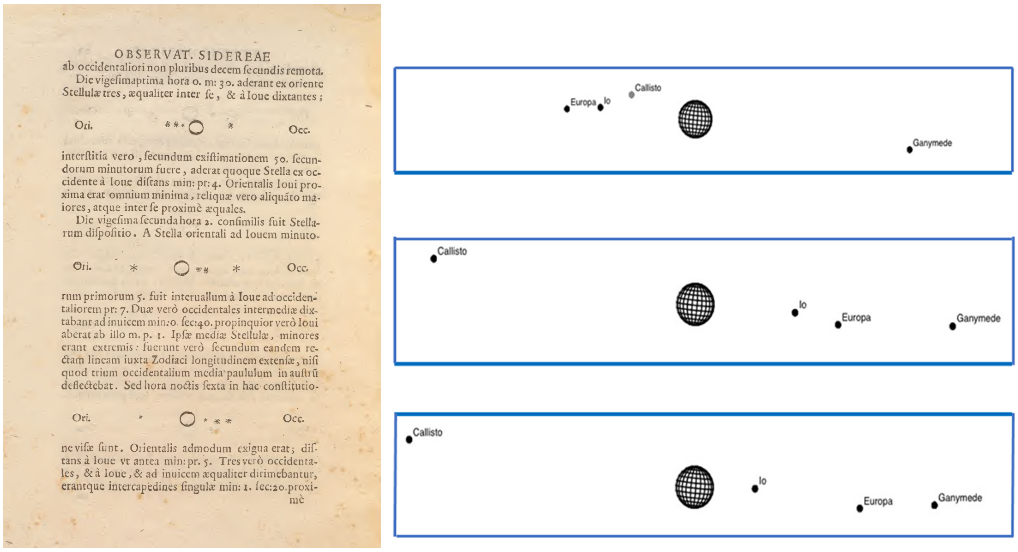
OPUS uses a RESTful API, so that the search is encoded in the following URL: https://opus.pds-rings.seti.org/#/instrument=Cassini+UVIS&time1=2005-06-21T00:00:00.000&time2=2005-06-21T04:00:00.000&qtype-time=any&unit-time=ymdhms&cols=opusid,instrument,planet,target,time1,observationduration&widgets=time,instrument&order=time1,opusid&view=browse&browse=data&cart_browse=gallery&startobs=1&cart_startobs=1&detail=

Figure 10. Step-by-step instructions on how to find and obtain UVIS data from the PDS via RMS OPUS for an observation of Saturn's aurora carried out around 03:35 on day 172 of year 2005. All links in this figure were accessed on 30 October 2022.

3.2. Ephemeris Tools

RMS also maintains a suite of tools to assist planetary scientists in the planning, acquisition and interpretation of observations (https://pds-rings.seti.org/tools, accessed on 30 October 2022). These tools help users to understand the context of observations, by generating ephemerides for a planet or any of its moons as a function of time, or diagrams of a planetary system at specified times from various viewpoints, or diagrams tracking moons:

- Planet Viewer generates a diagram showing the appearance of a planetary system at a specified time. Bodies and rings are rendered with terminators and shadows as appropriate. The viewpoint can be Earth's center, a particular Earth-based observatory, JWST, HST, or a specific planetary spacecraft. Figure 11 shows diagrams from the Jupiter Viewer tool for the same approximate times of Galileo's observations of Jupiter and its four large moons in 1610.


OBSERVAT. SIDEREAE

ab occidentaliori non pluribus decem ſecundis remota.

Die vigeſimaprima hora o. m: 30. aderant ex oriente Stellulæ tres, æqualiter inter ſe, & à Ioue dixtantes;

interſtitia vero, ſecundum exiſtimationem 50. ſecundorum minutorum fuere, aderat quoque Stella ex occidente à Ioue diſtans min: pr: 4. Orientalis Ioui proxima erat omnium minima, reliquæ vero aliquãto maiores, atque inter ſe proximè æquales.

Die vigeſima ſecunda hora 2. conſimilis fuit Stellarum diſpoſitio. A Stella orientali ad Iouem minuto-

rum primorum 5. fuit interuallum à Ioue ad occidentaliorem pr: 7. Duæ verò occidentales intermediæ dixtabant ad inuicem min:o. ſec:40. propinquior verò Ioui aberat ab illo m. p. 1. Ipſæ mediæ Stellulæ, minores erant extremis: fuerunt verò ſecundum eandem rectam lineam iuxta Zodiaci longitudinem extenſæ, niſi quod trium occidentalium media paululum in auſtrũ deflectebat. Sed hora noctis ſexta in hac conſtitutio-

ne viſæ ſunt. Orientalis admodum exigua erat; diſtans à Ioue vt antea min: pr. 5. Tres verò occidentales, & à Ioue, & ad inuicem æqualiter dirimebantur, erantque intercapedines ſingulæ min: 1. ſec:20. proximè

Figure 11. Galileo Galilei's observations [47] on the nights of 21 and 22 January 1610 (**left**) and the corresponding diagrams from the RMS Node's Jupiter Viewer tool (**right**) for the same approximate observing times.

- Moon Tracker generates a diagram showing the apparent east–west motion of one or more moons relative to the disk of a planet, within a specified time period.

- Ephemeris Generator generates a table listing of useful information about the viewing geometry for a planet or any of its moons as a function of time. Users are free to specify which of a variety of useful quantities to tabulate (e.g., RA and dec, phase angle, ring opening angle, distance, lunar phase, etc.)

The tools are supported for many missions, including Juno, New Horizons, Cassini, Europa Clipper, JUICE, HST, and JWST, and offer temporal coverage between the years 1550 and 2650.

3.3. User-Directed Classification via Self-Supervised Learning

As useful as OPUS and Viewmaster are, the system requires the user to already have knowledge about what data they wish to obtain. The RMS Node is developing a pilot project in self-supervised learning [48], which we hope will eventually result in the ability to add search and classification capabilities based on features in the data. For example, users could identify similarities across objects, instruments, or wavelengths to focus on characteristics of interest to their investigations. This is one way in which machine learning methods can speed up the searching process and aid in discovery of relevant data sets.

3.4. Mission Pages

The PDS Discipline Nodes host a variety of mission-specific pages to help users access all data from individual missions. Legacy data from missions that were archived using the PDS3 standards are currently being migrated to the new PDS4 archive standard. Experienced users who are familiar with these missions may be better served by accessing the node pages directly; however, new users should start with the mission pages contain a wealth of background and contextual information that will aid them as they begin working with the mission data. Most mission pages serve as portals to instrument-specific data located at the DNs and cross-referenced through these mission pages.

An example set of detailed mission pages are those created for the Cassini mission, which generated 635 GB of science data from 12 instruments while orbiting Saturn for more than 13 years (2004–2017). Near the end of the mission, the Cassini Project in partnership with the PDS developed a set of mission web pages that organized the data by science discipline and included support data and tools to ensure long-term access to the Cassini data by future generations of researchers [49]. Mission data archived in the PDS are generally presented to the users by mission, and then organized by instrument. The Cassini web pages maintained by the Atmospheres Node (https://atmos.nmsu.edu/data_and_services/atmospheres_data/Cassini/sci-saturn.html, accessed on 30 October 2022) go beyond this structure to also provide a science-based thematic organization that contains numerous resources for accessing data concerning Saturn's interior and atmosphere. Additional mission pages for Cassini are maintained by the other relevant DNs (RMS (https://pds-rings.seti.org/cassini), accessed on 30 October 2022), SBN, IMG, and PPI).

The Juno mission is an example of an active mission (at the time of this writing), with accumulating datasets that continue to provide a wealth of new observations of the Jovian system. ATM serves as the lead PDS node for the Juno mission and coordinates the archiving of Juno data, which are distributed through the mission web page (https://pds-atmospheres.nmsu.edu/data_and_services/atmospheres_data/JUNO/juno.html, accessed on 30 October 2022). Links to the various instruments take users to corresponding pages at other nodes (e.g., IMG and PPI). These pages are designed to provide information about the mission and instruments to help users find and make use of Juno data.

3.5. Planetary Image Locator Tool (PILOT)

The Planetary Image Locator Tool (PILOT) (http://pilot.wr.usgs.gov, accessed on 30 October 2022) is a web-based interface [50] that provides access to a search tool for several PDS orbital image catalogs indexed by the Unified Planetary Coordinates (UPC) database [51]. The UPC database contains improved geometric, photometric, and positional information about planetary orbital image data, computed using a uniform coordinate system and the most up-to-date SPICE kernels. These improvements result in enhanced image metadata and enable the user's ability to identify desired images, extending beyond those provided by the PDS. Precise searches can be performed within PILOT on individual metadata fields stored in the UPC database. In addition, PILOT has access to browse images, links to the raw images, and label information that can help scientists and cartographers perform further investigations on the images. Although all data in the UPC and PILOT must be supported by a camera model that describes detailed instrument and target geometric behavior during image acquisition, together these services address ∼90% of the orbital image data for which Imaging node is responsible to the PDS. PILOT not only allows users to download select images either individually or through provided scripts to pull large sets of images, it also provides direct access to the Map Projection on the Web (POW) online tool. PILOT was developed and is maintained by the Cartography and Imaging Sciences Node to complement other node delivery services.

3.6. Map Projection on the Web (POW)

The Map Projection on the Web (POW) (https://astrocloud.wr.usgs.gov/, accessed on 30 October 2022) service [52,53] allows users to convert raw PDS images to science-ready, map-projected products. POW integrates PILOT [50] and the UPC [51], the Integrated Software for Imagers and Spectrometers (ISIS) package (https://isis.astrogeology.usgs.gov/, accessed on 30 October 2022) [54], Geospatial Data Abstraction Library (GDAL) (https://gdal.org/, accessed on 30 October 2022) [55], and the Astrogeology cluster for its processing and delivery needs. POW provides users with calibrated cartographic images that can be used readily for analysis of atmospheric dynamics, cloud morphology and change detection, merging of dissimilar instrument images, analysis in a Geographic Image System (GIS) and use in a host of other scientific applications (e.g., ArcMAP, ENVI, Matlab, JMARS, QGIS, etc.). POW allows researchers to make use of a wealth of PDS science data without having to install or learn how to run ISIS and to benefit from a recommended processing pipeline as defined by USGS and the instrument teams. This service can also be used as a learning tool or an introduction to ISIS for those who would like to run it locally because the ISIS commands will be logged and delivered to the user. Using the POW front-end, a user is allowed to (1) select and submit a list of up to 250 PDS raw images, (2) define an output map projection and its parameters (e.g., Polar Stereographic, Sinusoidal), (3) define the output bit type (8, 16, or 32 bit), and (4) select an ISIS or PDS output format or a more standardized geospatial format such as GeoTiff, PNG, or JPEG. Conversion to the various supported image formats will be completed using the GDAL, which passes all cartographic information into the output format.

3.7. Planetary Image Atlas

The Atlas (https://pds-imaging.jpl.nasa.gov/Atlas, accessed on 30 October 2022) [56] provides access to the full collection of PDS-IMG data available in online holdings and data node catalogs. The Atlas uses faceted navigation to support searches on common search criteria such as mission name, instrument name, target, product type, observation/illumination geometry metadata, geographic coordinates, time constraints, etc. The Atlas also allows users to search images based on their "content" (i.e., moons, rings, clouds) through the use of deep convolutional neural networks to classify images [57,58].

4. Discussion

Looking forward, the PDS will be the primary repository for giant planets data from several upcoming missions and derived datasets, as well as supporting research conducted to aid in the interpretation of the remotely sensed giant planets data already archived in the PDS.

4.1. Future Mission Data

Juno began its extended mission phase in July 2021. The prime mission data, along with the accumulating data from the extended phase, will continue to be available from the PDS ATM, RMS, PPI, and IMG nodes. Higher order data products resulting from the end of the prime mission such as gravity model harmonic coefficients, auroral UV maps, auroral H_3^+ maps, magnetic field models among other products will also be available from the aforementioned nodes as they complete the peer review process and become ingested into the archive.

Beyond Juno, NASA's Europa Clipper and ESA's JUpiter ICy moons Explorer (JUICE) missions will conduct detailed investigations of several of Jupiter's icy satellites. If observations of Jupiter are also made, those data will be archived in the PDS in the relevant node(s) (or linked to from the PDS in the case of the JUICE data, whose primary archive will be ESA's Planetary Science Archive).

4.2. Data Derived from Analysis of Remote Sensing Observations

The scientific impact of giant planets remote sensing data in the PDS is felt long after the end of a mission. In some cases the data themselves are used for investigations long after their acquisition, making use of new analysis techniques, tools, or interpretations. In other cases the data are used to inspire new, related projects that enhance the interpretation of the original data. In these cases, the resulting data are often referred to as *derived data*, and ideally they should also be archived in the PDS to optimize their discoverability and usability.

There are numerous examples of derived data relevant to the giant planets that are archived in the PDS, for example, Saturn zonal wind profiles derived from Cassini ISS observations [59] and vertical profiles of Saturn's thermospheric temperature and H_2 densities derived from the analysis of Cassini UVIS and CIRS stellar occultation observations [60]. With the greater demand for archiving derived data products now being placed on researchers funded by NASA's Research and Analysis programs, the PDS expects to receive and archive numerous additional derived data products relevant to the giant planets. Both future data users as well as data proposers are encouraged to turn to the PDS as a logical repository for their derived data archiving needs.

4.3. Data Generated in Support of Giant Planet Studies

Laboratory experiments involving gases at or near conditions appropriate for the giant planets are required for the interpretation of remote sensing observations of the giant planets. For example, interest in hydrocarbons in the upper atmospheres of Jupiter and Saturn (and Titan) drove the need for better chemistry data to understand the behavior of these species in such extreme conditions [61]. The PDS archives laboratory data alongside the relevant mission and ground-based observatory data to aid in the advancement of the science of atmospheric chemistry in the outer Solar System.

Computational models and simulations are another critical tool used for the interpretation of remotely sensed giant planets data. Although model outputs are generally not archived in the PDS as they do not conform to PDS standards, several PDS nodes have implemented – or are now implementing – annex-style repositories to meet the data accessibility of the planetary modeling communities [62]. For example, the PPI Node maintains an annex (https://pds-ppi.igpp.ucla.edu/search/annex/, accessed on 30 October 2022) for models describing the Jovian current sheet and the global magnetic field of Saturn. The Atmospheres Node is in the process of implementing an atmospheric modeling annex that will be used to preserve outputs from atmospheric dynamical models, including those relevant to the giant planets.

4.4. Connections to Other Archives

In 2020 NASA chartered the Planetary Data Ecosystem (PDE) Independent Review Board (IRB) to provide a holistic evaluation of the planetary science community's access to and use of planetary data. The PDE IRB report provided scores of findings and recommendations aimed at fostering the development of the ecosystem and addressing barriers to data preservation and the use of planetary data [63]. The recognition that there is an entire ecosystem surrounding access to and use of planetary data was a critical outcome of the PDE IRB effort, as well as the need to improve the connectivity of the different elements of the ecosystem.

For example, data from the Hubble Space Telescope (HST) have led to many significant discoveries related to the giant planets during its 32-year (and counting) mission. These include the appearance and disappearance of dark vortices in the atmospheres of Uranus and Neptune [64], the unique nature of Saturn's aurorae [65], the long-term studies of the shrinking of Jupiter's Great Red Spot [28], and the changes in Jupiter's zonal wind profile [66]. The HST data, which are archived at the Mikulski Archive for Space Telescopes (MAST, https://archive.stsci.edu/hlsp/search.php, accessed on 30 October 2022), contains thousands of observations of the giant planets, but they are not integrated into PDS and are not easily searchable by planetary scientists.

The RMS Node is nearing completion of a pipeline to fully incorporate HST data identified as relevant to the Solar System into PDS4, with fully searchable OPUS metadata. The RMS pipeline can automatically query MAST, identify Solar System observations by a variety of attributes, retrieve the relevant files, and construct a corresponding PDS4 bundle that includes planetary metadata. When this project is complete, OPUS users will be able to access HST data based on a full set of Solar System-focused search attributes. In the meantime, RMS currently maintains a large collection of "placeholder" HST volumes (in PDS3 format). These contain browse products and metadata, but they redirect users to MAST to retrieve the actual data files. The foundation laid by this project will also enable the PDS to give similar treatment to JWST data.

In an effort to further improve interoperability, the PDS has played a major role in the development of the International Planetary Data Alliance (IPDA, https://planetarydata.org, accessed on 30 October 2022), whose goal is to facilitate access to and the exchange of planetary science data that are managed by a number of international space agencies. Enabling broad, international access to planetary data requires the use of common standards across the archives of different agencies (PDS4 has been adopted as the current standard for IPDA) and clear linkages among the data archives. Although the giant planets have yet to be explored by spacecraft managed by agencies other than NASA, that will change with ESA's JUICE mission, and the PDS will play a key role in ensuring transparent access to the JUICE data from the PDS.

Finally, with the discovery of thousands of giant planets in exoplanetary systems, there has been a tremendous increase in the number of studies that treat the giant planets of our Solar System as analogs for advancing our understanding of exoplanets. Current and future data in the PDS are vital to such studies, including for example full disk albedos of the giant planets [67,68], full-disk images of the giant planets acquired at a wide range of phase angles [69], and laboratory measurements made at giant planet and exoplanetary analog conditions [61]. Efforts are currently underway within NASA's Science Mission Directorate to enhance interoperability across the archives of the Astrophysics, Heliophysics, Planetary Science, and Earth Science Divisions. Exoplanet studies, which are heavily interdisciplinary in nature, are a motivating driver for such efforts and potential use cases are currently being explored.

5. Conclusions

The giant planets data within the PDS represent a record of an incredible human achievement: spacecraft exploration of the outer Solar System aimed at answering fundamental science questions concerning the origin and evolution of planets. The data also serve as the scientific legacy of numerous researchers who have contributed data they collected, analyzed, and used to generate new knowledge about the workings of the giant planets.

The data in the PDS are preserved using state-of-the-art information technology, with tools available to aid in their discoverability and usability. The fact that data from NASA's earliest days of giant planet exploration are still being used today to obtain new insights about the workings of the gas giants [70] demonstrates their long-lasting utility and benefit to science. The PDS will continue to uphold its role as NASA's preeminent archive for giant planets data while evolving to meet modern data archiving challenges and the changing needs of its user base.

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Abbreviations

The following abbreviations are used in this manuscript:

API	Application Programming Interface
ATM	Atmospheres Node
CDF	Common Data Format
CDF-A	Common Data Format Archival
CIRS	Composite Infrared Spectrometer (Cassini)
CODMAC	Committee on Data Management and Computation
Dec	Declination
DN	Discipline Node
DOI	Digital Object Identifier
DSN	Deep Space Network
ENA	Energetic Neutral Atom
EPN-TAP	EuroPlaNet Table Access Protocol
ESA	European Space Agency
EUV	Extreme Ultraviolet spectrographic channel of the UVIS instrument (Cassini)
FAIR	Findability, Accessibility, Interoperability, and Reuse of digital assets
FUV	Far Ultraviolet spectrographic channel of the UVIS instrument (Cassini)
GDAL	Geospatial Data Abstraction Library
GeoTiff	a standard geospatial format
GIS	Geographic Information System
HAPI	Heliophysics Application Programming Interface
HST	Hubble Space Telescope
IMG	Cartography and Imaging Sciences Node
INCA	Ion and Neutral Camera (Cassini)
IPDA	International Planetary Data Alliance
IPP	Imaging Photopolarimeter (Pioneer 10, 11)
IR	Infrared
IRB	Independent Review Board
IRIS	Infrared Interferometer Spectrometer and Radiometer (Voyager 1,2)

ISS	Imaging Science Subsystem (Cassini, Voyager 1, 2)
IVOA	International Virtual Observatory Alliance
JIRAM	Jovian Infrared Auroral Mapper (Juno)
JPEG	a common image format developed by the Joint Photographic Experts Group
JUICE	JUpiter ICy moons Explorer (European Space Agency mission)
JWST	James Webb Space Telescope
ISIS	Integrated Software for Imagers and Spectrometers
LORRI	Long Range Reconnaissance Imager (New Horizons)
LWIR	Long-Wave Infrared Spectrometer (several missions)
MAST	Mikulski Archive for Space Telescopes
MIMI	Magnetospheric Imaging Instrument (Cassini)
MVIC	Multispectral Visible Imaging Camera (New Horizons)
MWR	MicroWave Radiometer (Juno)
NASA	National Aeronautics and Space Administration
NIMS	Near Infrared Mapping Spectrometer
NSSDC	National Space Science Data Center
OPUS	Outer Planet Unified Search
PDE	Planetary Data Ecosystem
PDS	Planetary Data System
PDS3	Governing standards of the PDS from the mid-1990s until the adoption of PDS4.
PDS4	Current governing standards of the PDS, adopted in 2005
PI	Principal Investigator
PILOT	Planetary Image Locator Tool
PNG	Portable Network Graphic, a common image format
POW	Map Projection on the Web
PPI	Planetary Plasma Interactions Node
PPO	Planetary Period Oscillations
PRA	Planetary Radio Astronomy (Voyager 1, 2)
PWS	Plasma Wave Subsystem (Voyager 1, 2)
RA	Right Ascension
RMS	Ring-Moon Systems Node
RSS	Radio Science Subsystem (Cassini)
RSSN	Radio Science Sub-Node
RPWS	Radio and Plasma Wave Science (Cassini)
SBN	Small Bodies Node
SL9	Comet Shoemaker-Levy 9
SPICE	Observation geometry information system for planetary spacecraft
SSI	Solid State Imager (Galileo)
TOPCAT	Tool for OPerations on Catalogs And Tables
UPC	Unified Planetary Coordinates
URAP	Unified Radio and Plasma Experiment
USGS	United States Geological Survey
UV	Ultraviolet
UVIS	Ultraviolet Imaging Spectrograph (Cassini)
VIMS	Visual and Infrared Mapping Spectrometer (Cassini)

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