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The international outer planets watch atmospheres node database of giant-planet images

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ABSTRACT

The Atmospheres Node of the International Outer Planets Watch (IOPW, formerly known as International Jupiter Watch; Russell et al., 1990) intends to encourage and coordinate the imaging observations and study of the atmospheres of the Giant Planets. The main activity of the atmospheres node is to provide an interaction between the professional and amateur astronomical communities maintaining a large database of images of the giant planets (primarily Jupiter and Saturn but with increasing contributions of Uranus and Neptune too). The observational datasets of Jupiter and Saturn correspond to images obtained in the visible range (300 nm–1 μm), during the last decade, most of them performed by amateur observers. We here describe the organization and structure of the database as posted on the Internet and in particular the PVOL software (Planetary Virtual Observatory Laboratory) designed to manage the site in the spirit of the Virtual Observatory projects. We also describe with examples the important role of the amateur–professional collaboration in the study of the atmospheres of Jupiter and Saturn in an epoch of large telescopes and spacecraft observations of both planets.

1. Introduction

1.1. Origin of the IOPW

The International Outer Planets Watch is a program that was developed 25 years ago for the encouragement and coordination of the study of long-term temporal variations in the Outer Planets and their systems. It grew up from the International Jupiter Watch (Russell et al., 1990), which was initially intended to provide ground-based support to the Galileo mission to Jupiter and was later extended to study the Giant Planets. The IOPW is composed of a Steering Committee and six discipline working groups (Atmosphere, Aurorae, Io Plasma Torus, Laboratory and Theory, Magnetosphere and Radio Emissions and Satellite discipline). A global view of its organization can be seen at the webpage: http://www-ssc.igpp.ucla.edu/IJW/. Informal meetings between the nodes are organized at every annual meeting of the Division for Planetary Sciences of the American Astronomical Association.

1.2. Atmospheres node: professional–amateur collaboration

Since Jupiter and Saturn are large and bright objects in the night-sky, imaging them is a relatively easy task. The Atmosphere node has become a well-suited place for a broad collaboration between amateur and professional astronomers. Historically, throughout the 20th century amateur astronomers have played an important role in the study of the morphology and motions of large atmospheric features in Jupiter and Saturn. An example of their contribution to Jovian research can be found in the books by Peek (1958) and Rogers (1995) under the umbrella of the British Astronomical Association (BAA). Other amateur societies regularly compile and analyze images of the planets, most detached by their contribution is ALPO (Association of Lunar and Planetary Observers) in the US and Japan. The JUPOS Database for Objects Positions on Jupiter (http://jupos.privat.t-online.de/index.htm) is devoted to measurements of the position and motions of Jovian features, and it is another example of a useful scientific amateur contribution.

The development of the CCD imaging techniques along the 80's produced a first revolution in the amateurs contribution to the survey of atmospheric phenomena in the planets, in particular in the early 90's when CCD cameras became available for the amateur community replacing the classical photographic imaging.

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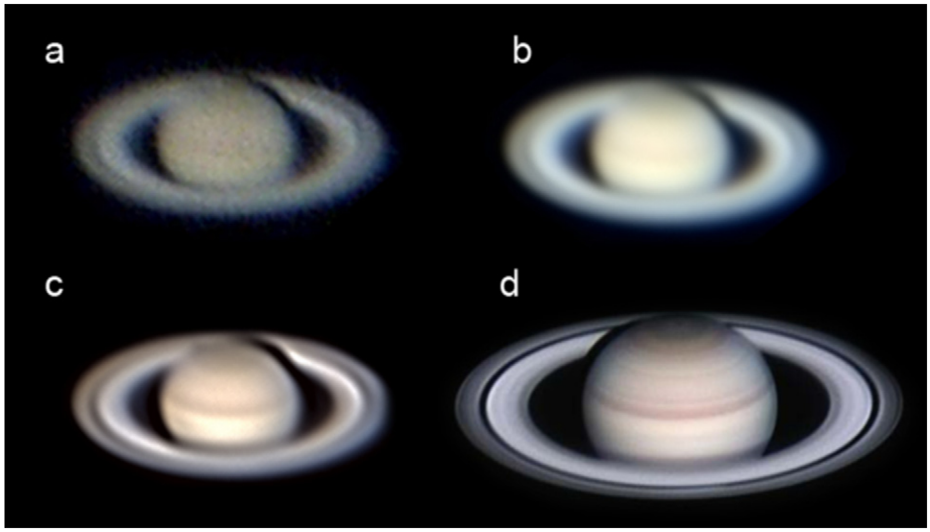

Fig. 1. Illustration of the lucky imaging technique and its performance. (a) Single short exposure of Saturn. (b) Stacking of 400 short exposures with an improved signal to noise ratio. (c) Wavelet processed image after stacking 6000 consecutive frames. Images (a)–(c) were acquired by A. Sánchez de Miguel on April 6, 2004 from Universidad Complutense in Madrid with high levels of light pollution. Still many details in the atmosphere and the rings can be seen in the final image. Better final images can be obtained by selecting only the best images of the observing sequence and carefully processing the final stacked image. (d) Image obtained on October 28, 2003, by Damian Peach, using a Celestron 11″ SCT and a ToUcam Pro combining 3000 thousand 1/5th-second exposure frames.

A second revolution occurred around 2000 when "lucky imaging techniques" (Law et al., 2006) became popular among the amateur community for high-resolution imaging of the planets (Cidadao, 2001; Grafton, 2003; Buick, 2006). These techniques consist of taking many short exposures of a bright object where the turbulence effects on the image are frozen by the short exposure. The images are then examined automatically by appropriate software that chooses the best defined images, aligns the images chosen and stacks them in a final image.[1] When the read-out noise of the detector is low enough the final image has a high signal to noise ratio, which is almost unaffected by atmospheric turbulence and in principle is able to reach the diffraction limit of the telescope. Fig. 1 shows a representative example of the procedure. The method allows reaching diffraction limited resolution, and comparison with images obtained by large telescopes years ago shows that currently a 40-cm telescope is able to retrieve features in Jupiter that the 5-m class telescopes were not able to gather using classical photographic methods.

A large expertise in this field is now available in the amateur community and a large number of observers around the world are able to obtain high-resolution images of Jupiter and Saturn with modest to moderate equipment and telescopes with objective diameters in the 20–40 cm range. It must be noted that not only the giant planets are targets for this effort of planetary atmospheres surveys, but Venus and particularly Mars are other favourite objects. As an example, Barentsen and Koschny (2008) describe an online archive of ground-based observations of Venus motivated by the Venus Express mission designed to increase the usability of those observations for scientific purposes. ALPO and other associations also have imaging archives of these two planets.

The atmospheres of the giant planets display a wide spectrum of variability in the temporal and spatial scales, from hours to years and from the mesoscale to the planetary length scale. The yearly increased number of observers and their capability to observe Jupiter and Saturn on a nearly continuous basis from different locations in the Earth provide a long and time-resolving survey of them that have resulted in discoveries of time-critical phenomena just after their origin and with a fairly good temporal coverage of their long-term evolution. Representative examples are the eruption of convective phenomena as the rare event of the Great White Spot in Saturn in 1990 (Sánchez-Lavega et al., 1991a), the eruptions and planetary-scale disturbances of the North Tropical Belt of Jupiter (Sánchez-Lavega et al., 1991b; Sánchez-Lavega et al., 2008a), and most recently, the discovery of a cometary–asteroidal impact in Jupiter in July 2009 performed by A. Wesley only hours later the actual impact actually happened (Sánchez-Lavega et al., 2010). The discovery and long-term analysis of the evolution of such events show the importance and validity of amateur observations of the Giant Planets in the spacecraft era, as well as their future utility.

In this paper we present the IOPW atmosphere node online database of images of the Giant Planets. We describe the database and the software managing it in Section 2, we describe the datasets available in Section 3, we assess the scientific value of monitoring the atmospheric activity of Jupiter and Saturn with these observations in Section 4 and we present our conclusions in Section 5. Planet images in this paper are oriented in the traditional view of the amateur astronomical community with the South up and longitudes increasing from left to right.

2. The PVOL system

Before 2003 the traditional IOPW atmospheres node webpage http://www.ehu.es/iopw/ consisted of several webpages storing amateur observations of Jupiter and later Saturn, Uranus and Neptune. The first database was located at the New Mexico State University under the leadership of R. Beebe and later M. Vincent and moved afterwards to the Universidad del País Vasco. The observations were available as jpg or gif files ordered in terms of the planet and the date and time. Systematic searches of large number of images were difficult but also of specific data. Starting in 2003 we developed a database web server for images of the giant planets. The system is inspired by Virtual Observatory concepts (Szalay and Gray, 2001; Graham et al., 2008) and is called PVOL (Planetary Virtual Observatory & Laboratory) being available on http://www.pvol.ehu.es. Fig. 2 shows a snapshot of the PVOL entry page. The aim of this service is to store the

[1] The freely available software RegistaX is probably the most popular software for that purpose. http://www.astronomie.be/registax/.

Fig. 2. Screenshot of the PVOL homepage hosting the database.

increasing number of image files obtained by the large community of amateur astronomers providing a friendly but powerful search capability of the stored observations. An example of a query to the database and the data retrieved from the database is given in Fig. 3.

The PVOL software is programmed using Java for all the background processing, and simple Structured Query Language (SQL) for the queries to the database. The web server is Apache-HTTPd 2.0 web with an Apache-Tomcat 5.5 servlet engine and a MySQL server database system. The system incorporates a search engine that allows a search for images based on different criteria (date/time/filter/author) and also for Central Meridian longitudes in reference systems I, II and III for Jupiter and I and III for Saturn. These are the classical longitude systems employed to locate features in both planets due to their dominant zonal (East–West) motions. This is a nice and useful feature when studying a particular region of the atmosphere (for example for long-term tracking of particular vortices like the Great Red Spot or Oval BA in Jupiter). Although a single image per file is recommended many contributors incorporate several images into one single file imposing difficulties when dealing with such files. Because of that it is not possible to assign a single central longitude to every image file and the PVOL system uses two independent databases both searchable. The IOPW database is the complete database containing all the images. The PVOL database was designed to provide more accurate searches allowing identifying images obtained with a particular filter and containing specific longitudes. As such, it was initially intended to contain only one image per file. However the large amount of images stored and received by different observers made this approach impractical, and currently the PVOL database also contains a small number of image files with several images by the same observer obtained close in time.

Individual observers can register in the system and upload their images to the database. They can also access their data through an application in the web server called My PVOL (http://www.pvol.ehu.es/index.jsp?action=mypvol). Alternatively they can e-mail the observations to the web administrator for daily to weekly updates of the web server. Backups of the database are programmed every midnight with a full backup of images and database every Sunday midnight.

The database also supports more sophisticated web browser searches by using a Virtual Observatory Table (VOTable—http://www.ivoa.net/Documents/VOTable/). A VOTable is a flexible exchange format for tabular data using XML standard labels as defined by the International Virtual Observatory Alliance (IVOA). The system generates VOTables of sets of observations meeting particular criteria. For example, a user who wishes to get a report about images of Uranus in the database can generate a full table of all the images by typing a simple URL that look like this: http://bppx90.bp.ehu.es:8080/pvol/getVOTable?TARGET=Uranus

Table 1 provides a list of valid fields to search and examples of VOTable queries.

3. Data in the PVOL system

3.1. Observers and telescopes

We incorporated all the observations from the year 2000 onwards reported to the IOPW atmospheres node in this web service. Most of the observations come from amateur astronomers but there are also contributions from the Pic du Midi Observatory 1-m Solar System dedicated telescope (France), the IAC 80 cm telescope at Teide Observatory (Canary I., Spain) and some examples of NASA-IRTF Observatory (Mauna Kea, Hawaii) images of Jupiter. Representative examples of the images in the database are shown in Fig. 4 for Jupiter, Saturn and Uranus. At present, there are about 200 observers and amateur organizations contributing observations to the database from many latitudes and locations around the world. Fig. 5 shows the locations of the most active observers contributing to the PVOL–IOPW database. A nearly full longitudinal coverage of the Earth is accomplished with a reasonably good distribution of observers at both North and South hemispheres. Most of the images sent to the IOPW are composed of RGB color frames obtained in broadband filters in jpg format. Some observers also supply individual filtered images and others provide images in filters coupled to the strong methane

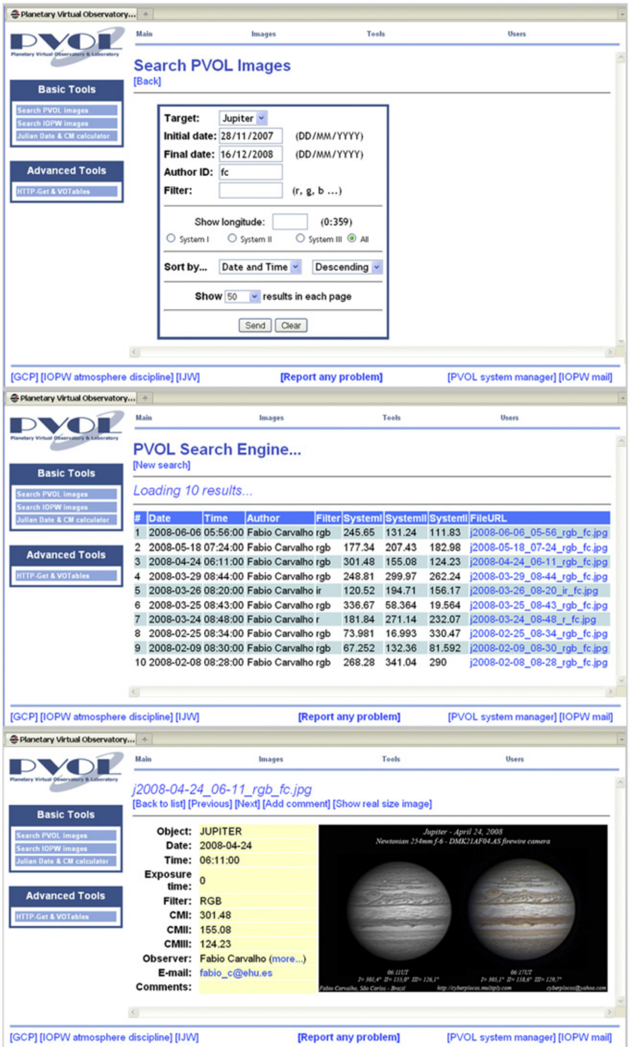

Fig. 3. Example of a query to the database (top panel) requesting observations of a particular observer, Fabio Carvalho, between two dates, the result of the query (middle panel) with a summary information about the images and one of the images from the selection (below).

Table 1
Valid fields in queries using VOTable.

Field name	Explanation	Requirements
TARGET	Target of the image	(Jupiter, Saturn, Uranus, Neptune)
SDATE	Minimum date	[dd/mm/yyyy] format, optional field
FDATE	Maximum date	[dd/mm/yyyy] format, optional field
SORT	Sort by	[OBS, FILTER] if nothing is defined, the result is sorted by date and time, optional field
OBS	Observer	User code, optional field
FILTER	Filter used	r, g, b, rgb, rgbhc, cl, optional field

Examples of VOTable queries

Looking for images of Saturn taken by Jesus R. Sanchez after October 1st, 2004: http://bppx90.bp.ehu.es:8080/pvol/getVOTable?TARGET=Saturn&OBS=Jesus&SDATE=01/10/2004

Looking for images of Saturn taken before February 1st, 2002 with a blue filter: http://bppx90.bp.ehu.es:8080/pvol/getVOTable?TARGET=Saturn&FDATE=01/02/2002&FILTER=b

Looking for images of Uranus, sorted by observer: http://bppx90.bp.ehu.es:8080/pvol/getVOTable?TARGET=Uranus&SORT=OBS

absorption band at 890 nm, which is of particular interest to study atmospheric features extending high in the atmosphere to the tropopause level. Individual images are the result of severe image processing of the original observation. Although this is fine when using the images for dynamical studies, it is a big problem for calibration of the images and studies of cloud reflectivity, color characterization or cloud structure modeling. However many observers conserve their original images in fits format (retrieved after the process of align and stack individual frames) and can be contacted for retrieval of the original data.

3.2. Data: amount, distribution and quality

The PVOL database is probably the largest database of images of Jupiter and Saturn in the visible and although irregular in coverage and image quality it provides a nearly timeline continuous coverage of both planets since 2000. The database is freely accessible by anyone and is open to contributions from new observers. Currently the total number of image files is of the order of 9000 but many of these contain several observations of the same night by the same observer at different times. The total amount of data occupies a storage volume of about 1.5 Gb and is organized in observations campaigns. Each observing campaign is the $\sim$9 months period when the planet is observable from the Earth and is determined by the planet opposition. Table 2 summarizes the number of available images in each apparition of each planet. Fig. 6 shows the temporal distribution of observations in Jupiter and Saturn apparitions beginning in the year 2000. The quality of the observations varies widely from one observer to other depending on observer location and planet declination, atmospheric seeing, equipment and observer experience. One of the tools in the search browser is to search for observations of particular observers. Also there is a steady improvement in image quality from the early images in 2000–2005 with the image quality increasing more slowly since then. This is caused by the different generations of cameras used by most observers (from simple webcams used in early 2000 to more sensitive specially designed cameras with sensitivities currently down to 0.03 lux and able to obtain videos of up to 45–60 frames per second) and continuous improvement in software processing and observer experience. Fig. 7 shows representative examples of Jupiter best images imaged close to opposition from a single observer.

Lucky imaging allows, under high quality skies, obtaining images to the diffraction limit. For a 25 cm aperture telescope observing in the visible (500 nm) this results in a maximum resolution limited only by diffraction of the order of 0.5 arcsec, which translates in spatial resolutions of 1400 km for Jupiter and 3000 km for Saturn at the sub-Earth observing point when the planet is close to opposition in both cases. For a 38-cm-aperture telescope these numbers improve to 860 and 1800 km, respectively.

The number of observations of Jupiter and Saturn per observation campaign available in the PVOL server is given in Table 2 and shown graphically in Fig. 8. Both datasets follow an exponential growth roughly akin to Moore's law (Moore, 1965) with an average time of 6 years for doubling the annual number of observations. This is related with the fact that, except for the optics, the detector and processing technology are both dependent on Moore's law (the Moore law has a doubling time of processing power and hard-disk storage of 2 years) although it is modified by the position of the planet in the night-sky and the motivations of observers. For instance, trends observed on the data is the fast increase of Saturn data before the Cassini mission (doubling time of images in periods of 1 year) and the decline of

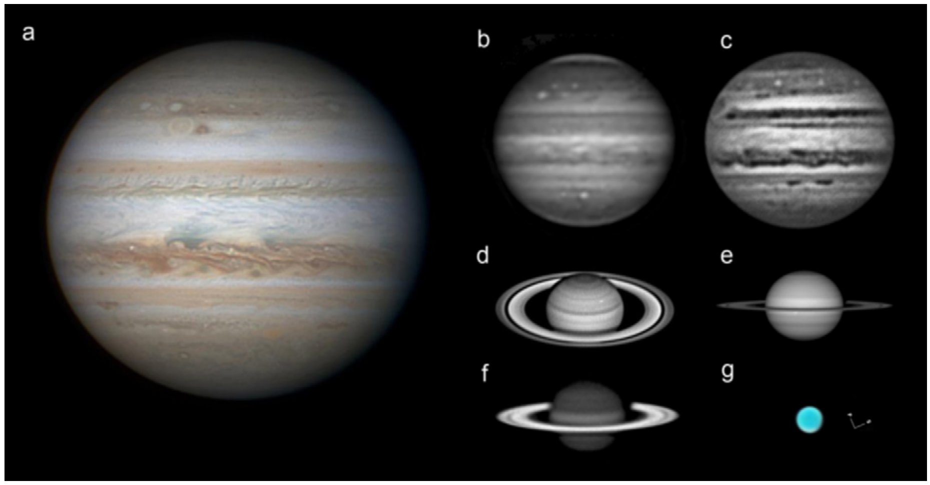

Fig. 4. Representative examples of Jupiter images in the PVOL data server. (a) RGB composite image of Jupiter obtained on October 20, 2009 by A. Wesley. (b) Methane-band image of Jupiter obtained by D. Peach on August 23, 2009; images in this filter show the hazes and high altitude clouds. (c) Image obtained in the narrow OIII filter (wavelength 500.8 nm) in the IAC80 telescope (Teide Observatory) on August 27, 2009. This filter produces sharp images of the atmosphere but despite the large size of the telescope this image is only obtained after stacking 7 individual frames. (d) Monochrome image of Saturn obtained on December 13, 2003 by J. R. Sánchez showing a bright storm in the South hemisphere storm alley. (e) Monochrome image of Saturn obtained on April 5, 2009 by D. Peach showing a distinctive convective equatorial feature. (f) Methane-band filter (wavelength 890 nm) image of Saturn obtained on May 5, 2009 by D. Parker showing again the band-zone structure. (g) RGB image of Uranus obtained on September 8, 2006 by D. Parker with structures on the equatorial limbs.

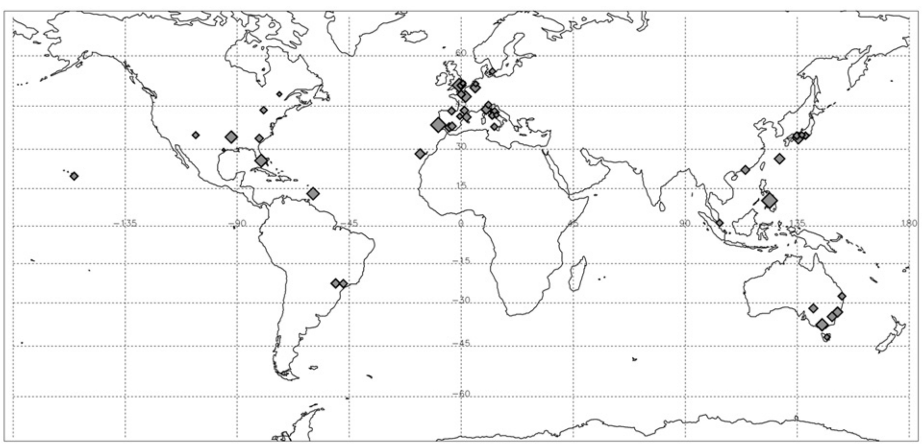

Fig. 5. Map of locations of IOPW–PVOL active contributors. For simplicity only those observers with more than 20 contributions to the Jupiter database are shown. The size of each point scales with the logarithm of the number of observations for each location sometimes incorporating several observers at the same city.

Table 2
Planet images per observing campaign.

Planet	Campaign	Number	Planet	Campaign	Number
Jupiter	2009–2010[a]	1279	*Saturn*	2008–2009[a]	217
	2007–2009	1158		2007–2008	176
	2006–2007	1414		2006–2007	170
	2005–2006	908		2005–2006	261
	2004–2005	892		2004–2005	444
	2003–2004	650		2003–2004	230
	2002–2003	671		2002–2003	123
	2001–2002	559		2001–2002	24
	2000–2001	293		–	–
Total:	**7824**	**Total:**		**1645**	
Uranus	2002–2008[a]	**58**	*Neptune*	2002–2008[a]	**9**

[a] As of 13 January 2010.

observations of Saturn as the Cassini mission entered into orbit in 2004 making amateurs move to other observing projects. This effect was also combined with the lower declination of Saturn after 2004 hindering observations from observers in the North-hemisphere mid-latitudes. There is also a slow decrease in the number of observations of Jupiter in the last two years due to Jupiter's southern declination and also related with the increasing custom by amateurs of posting their images in personal webpages or astronomical association forums instead of reporting them to a central repository.

The variation of the declination with time of each planet favours different observing latitudes in different planet apparitions. Fig. 9 shows the declination of Jupiter and Saturn for the last and next decades. Both planets are currently best observed from equatorial latitudes; while Jupiter will be best observed from North tropical latitudes, Saturn will be best observed from South tropical latitudes in the next few years. The capability of the amateurs of providing a large network of observing sites accommodates well with the range of planet declinations.

4. Scientific usability of the data

The higher-resolution images in the database serve as support for dynamical studies of the atmospheres of Jupiter and Saturn. The main drawback is the lack of intensity calibration of the images. The following is a list of scientific topics that can be addressed with a long-term, fine time coverage, high-resolution images of Jupiter such as those in the IOPW–PVOL database (other useful contributions can be seen in Rogers, 1995).

- Long-term studies of "oval spots" (vortices). These include: interactions such as approaching ovals and final mergers as occurred for the long-lived White Ovals BC, DE, and FA that finally lead to BA (Sánchez-Lavega et al., 1999, 2001), the interaction and engulfment of large tropical ovals by the Great Red Spot (GRS) (Sánchez-Lavega et al., 1998; Sánchez-Lavega et al., 2008b), the motions and oscillation of the GRS (Trigo-Rodriguez et al., 2000), and long-term motions and color changes as that of BA (García-Melendo et al., 2009). For instance the reddening of oval BA was first reported by amateur astronomer C. Go from Philippines (Naeye, 2006; Go et al., 2006) and alerted the international community to perform dedicated observations on large telescopes such as Keck and HST also motivating part of the high-resolution observations performed by the New Horizons spacecraft during its Jupiter flyby (Cheng et al., 2008; Hueso et al., 2009; Pérez-Hoyos et al., 2009).

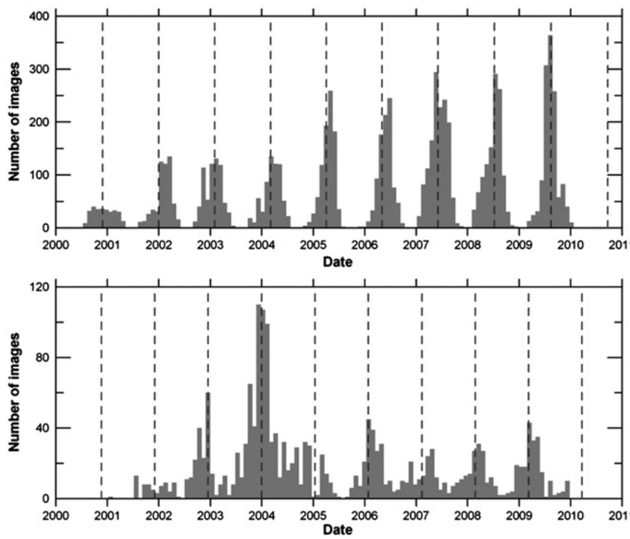

Fig. 6. Long-term monitoring of Jupiter's (upper panel) and Saturn's (bottom panel) atmosphere from IOPW–PVOL observations. The number of observations is binned every month. Vertical dashed lines show the planetary oppositions for each observing campaign.

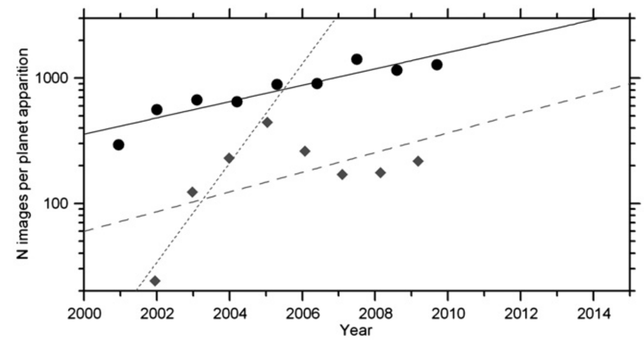

Fig. 8. Number of images per observation campaign of Jupiter (circles) and Saturn (rhombs) in the IOPW database. Dates for each year are taken at the planet opposition. In both cases, the number of observations per campaign follows a rough Moore law (dashed lines) with a required time for doubling the number of observations per year of the order of 6 years. Saturn observations increased at a rate of doubling the observations every year in the period 2001–2004 (dotted line) and peaked in December 2004–January 2005 but they later decreased corresponding to the decrease in altitude of Saturn in the North-hemisphere night-sky.

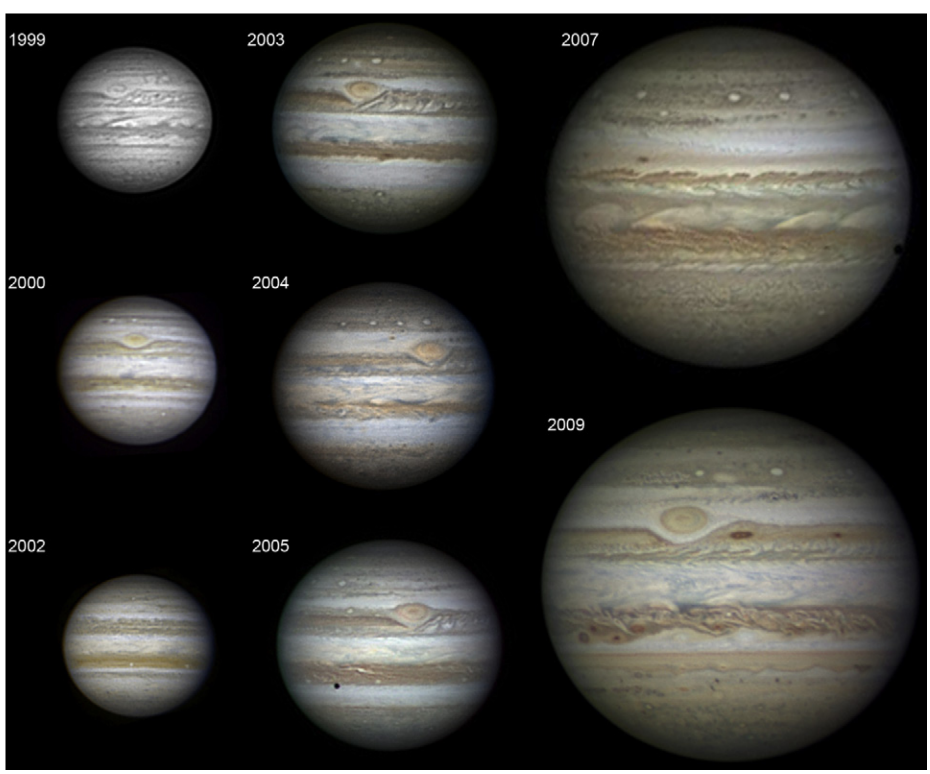

Fig. 7. Continuous improvement in quality of images from 1999 to 2009. All observations are by D. Peach observing with a variety of 9.25–12″ telescopes and cameras at United Kingdom, Canary Islands and Barbados. Data from 2008 is not included because for this observer Jupiter was only imaged from United Kingdom with Jupiter never higher than 16° altitude. Images have been rescaled according to the amount of detail visible on the images.

- Long-term monitoring of the morphology and drift rate of long-lived equatorial hot-spots (Arregui et al., 2006).
- Survey of large storm activity in Jupiter. Convective storms are common in the North–West side of the Great Red Spot and the North Equatorial Belt and appear also on other latitudes like in the recent 2007 convective eruption of the North Temperate Belt (Sánchez-Lavega et al., 1996, 2008a).
- Search for unpredicted cometary–asteroidal impact features on the atmosphere. The July 2009 impact in Jupiter was discovered by A. Wesley using a 14.5″ Newtonian telescope and continued to be observable by most amateurs over a 3-month period. It was monitored for a longer time-basis with professional telescopes using near infrared observations in methane absorption bands of varying strengths. Since this is the second impact observed in Jupiter in 15 years it is worthy to monitor Jupiter on a nearly continuous base to improve statistics about impacts on the outer solar system (Sánchez-Lavega et al. 2010). For impactor sizes of 0.5 km and larger this kind of survey is clearly achievable with images from the IOPW–PVOL database.

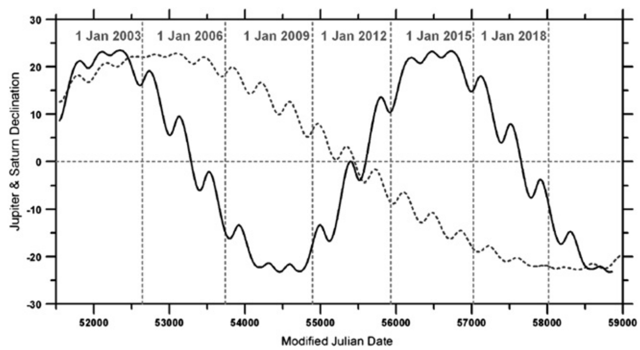

Fig. 9. Declination of Jupiter (dark solid line) and Saturn (lighter solid line) for the last and next decades.

The database observations of Saturn are limited by a typical spatial resolution of ~2000 km per pixel and the lower contrast of cloud features in the visible range. The main topics that can be addressed for Saturn are as follows:

- Characterization of belt-zone reflectivity changes in different years along the Saturn seasonal cycle (Pérez-Hoyos et al., 2006). Those changes in the belts and zones locations are related to seasonal changes of the vertical cloud structure and therefore of maximum interest for the understanding of the atmospheric response to insolation changes.
- Survey of the eruption and evolution of convective storms as the Great White Spots (Green, 1990; Sánchez-Lavega et al., 1991a) and other lower-scale features—ovals and storms- (Sánchez-Lavega et al., 2004; Fisher et al., 2008).

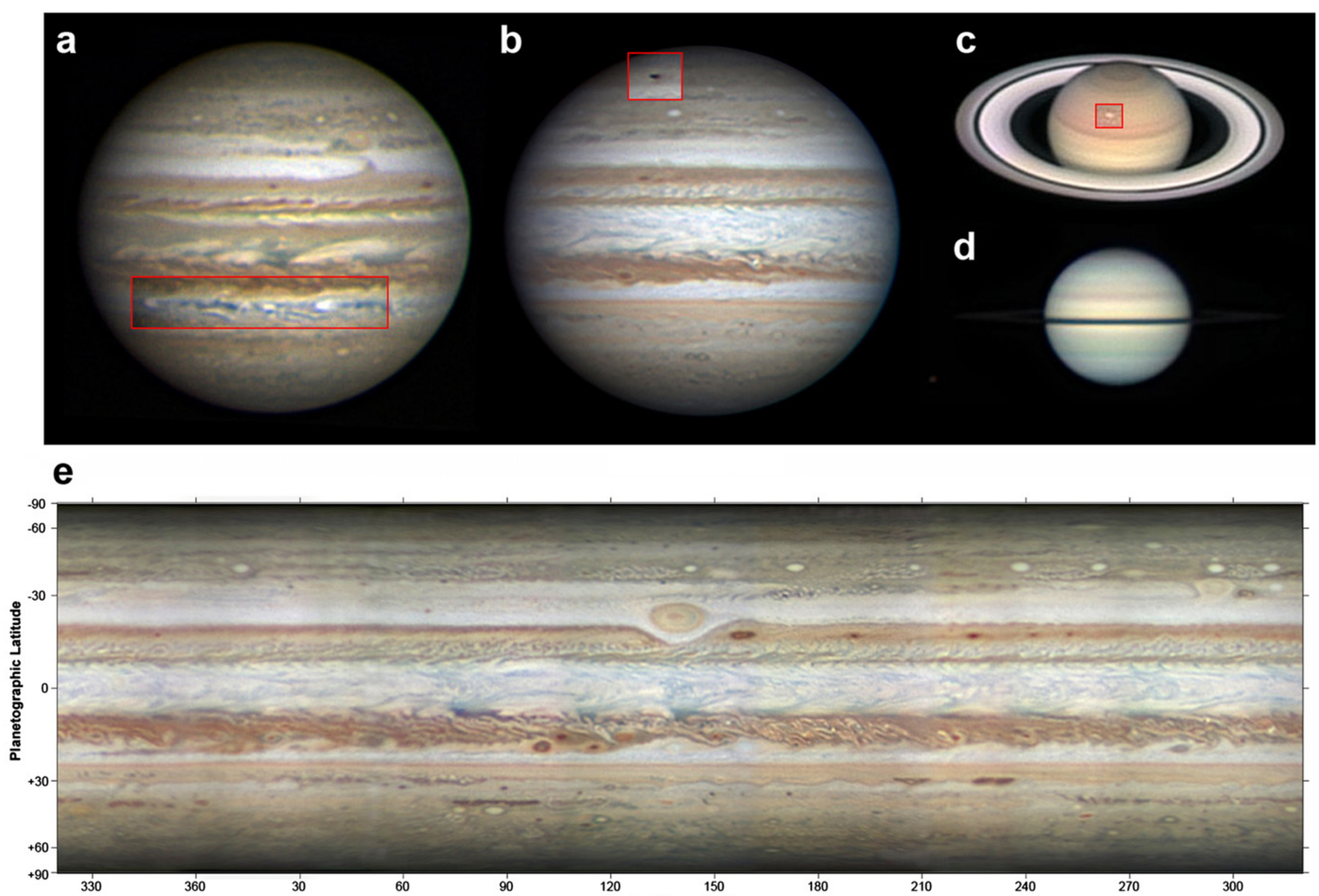

Fig. 10. Examples of scientific themes addressable with IOPW images. (a) Development of a global disturbance in the North Temperate Belt of Jupiter. The disturbance appeared as two bright plumes followed by turbulent on their wake. Image acquired by Zac Pujic on April 5, 2007. (b) The July 2009 impact on Jupiter imaged by A. Wesley on July 19, 2009 only hours after the impact. (c) A Saturn mid-latitude storm observed on December 22, 2002 by E. Grafton. (d) Saturn ring crossing observed by A. Wesley on July 18, 2009 with a Sun–Saturn separation of 52° and a planet altitude of 38°. (e) Full cylindrical projection of several images obtained during a Jupiter rotation on September 10–11, 2009 by D. Peach.

Fig. 10 shows examples of images available in the database addressing these scientific themes. In both planets, observations by amateurs have provided the basis for much of the application time for observations with large research facilities like Hubble Space Telescope or Keck Telescope.

5. Concluding remarks

The IOPW–PVOL database stores observations from hundreds of contributing observers covering almost a decade of atmospheric phenomena on Jupiter and Saturn. The current network of amateur observers and their advanced use of fast repetition cameras with image processing techniques provide an excellent time-basis for the survey of atmospheric phenomena and support their research with largest telescopes that cannot be dedicated in a continuous manner to this task. Observations with small telescopes provide not only the temporal context for interpreting the high-resolution observations obtained from large telescopes or space missions but in many cases also the motivation to obtain higher-resolution data. The ensemble of observations in the IOPW–PVOL database has provided to be very valuable in the study of the atmospheres of Jupiter and Saturn. In particular the continuous observations from amateurs have resulted in discoveries of time-critical phenomena on Jupiter. The database is freely usable, open to more contributors and to the use of the data by research teams.

With the probable end of the Cassini Equinox mission in 2017 and the decommissioning of the Hubble Space Telescope around 2014, high-resolution observations in the visible range of both Jupiter and Saturn must rely on observations performed only from the ground. Support for new missions such as Juno (to be launched in 2011 and arrive in 2016) and the Europa Jupiter System Mission (EJSM, to be launched around 2020) will have to be anticipated in advance. A dedicated 1-m class telescope with a planetary camera for lucky imaging could provide a splendid support for these missions (Wesley et al., 2009). Perspectives of past and future ground-based support of space missions are given by Orton (2009).

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