

The need for professional–amateur collaboration in studies of Jupiter and Saturn

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The observation of the gaseous giant planets is of high scientific interest. Although they have been the targets of several spacecraft missions, there still remains a need for continuous ground-based observations. As their atmospheres present fast dynamic environments on varied timescales, the availability of time at professional telescopes is neither uniform nor of sufficient duration to assess temporal changes. On the other hand, numerous amateurs with small telescopes (with typical apertures of 15–40 cm) and modern hardware and software equipment can monitor these changes daily (within the 360–900 nm wavelength range). Amateur observers are able to trace the structure and the evolution of atmospheric features, such as major planetary-scale disturbances, vortices, and storms. Their observations provide a continuous record and it is not uncommon to trigger professional observations in cases of important events, such as sudden onset of global changes, storms and celestial impacts. For example, the continuous amateur monitoring has led to the discovery of fireballs in Jupiter’s atmosphere, which provide information not only on Jupiter’s gravitational influence but also on the properties and populations of the impactors. Photometric monitoring of stellar occultations by the planets can reveal spatial/temporal variability in their atmospheric structure.

Co-ordination and communication between professionals and amateurs is therefore important. We present examples of such collaborations that: (i) engage systematic multi-wavelength observations and databases, (ii) examine the variability of cloud features over timescales from days to decades, (iii) provide, by ground-based professional and amateur observations, the necessary spatial and temporal resolution of features that will be studied by the interplanetary mission *Juno*, (iv) investigate video observations of Jupiter to identify impacts of small objects, (v) carry out stellar-occultation campaigns.

1. Introduction

Collaboration between amateur and professional astronomers is increasingly important in many areas of solar system science.^{1,2} In this paper we focus on the gaseous giant planets. For both professionals and amateurs, the overarching goal of observations is to understand the atmospheres of the giant planets, which are so different from Earth, and so typical of many planets now being discovered around other stars.

Jupiter and Saturn have been observed intensively for over a century. There are historical accounts of these observations in publications, most of which are by the British Astronomical Association (BAA),³ Association of Lunar and Planetary Observers (ALPO),⁴ Association of Lunar and Planetary Observers of Japan (ALPO Japan)⁵ and Société Astronomique de France (SAF).⁶ In recent years amateurs have captured numerous high-resolution images as a result of the advancement of technology, providing near-continuous coverage in visible and near-infrared wave-bands.

Meanwhile, professional astronomers have long-term observational programmes to observe the giant planets with NASA’s InfraRed Telescope Facility (IRTF) and the Pic du Midi 1 m telescope. Observations are also made using the *Hubble Space Telescope* (*HST*), Subaru telescope of the National Astronomical Observatory of Japan and the European Southern Observatory’s Very Large Telescope (VLT). However, most of these are directed

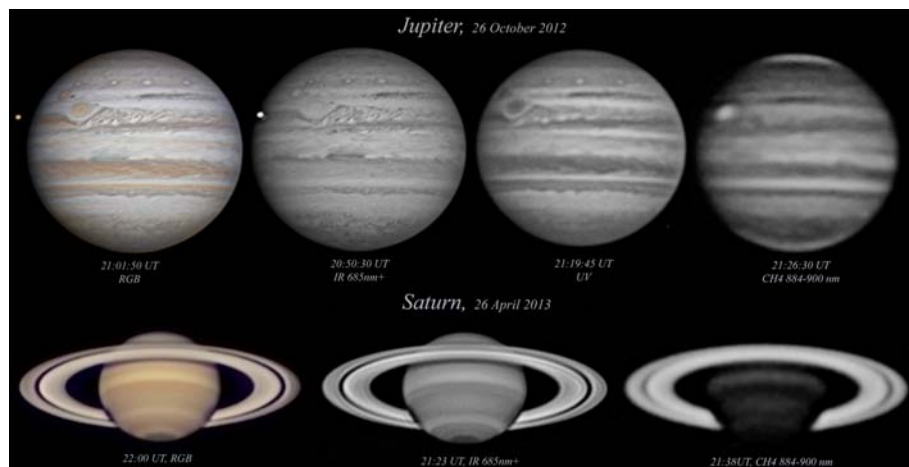


Figure 1. A set of images showing the different aspects of Jupiter (*top*) and Saturn (*bottom*) according to wavelength by co-author E. Kardasis (South is up).

to the giant planets only intermittently (largely due to intense competition for time) and mainly at infrared wavelengths. Several spacecraft have also visited each planet, and the *Cassini* spacecraft is operating in orbit around Saturn as of this writing.

Even though the professional ground-based and spacecraft observations provide a large variety of spectral and temporal data, the amateur network of more than 100 observers around the world still provides professionals with important types of information: complementary wavelength coverage to professional near- and mid-infrared observations; global coverage and context for their observations; independent verification and confirmation of their

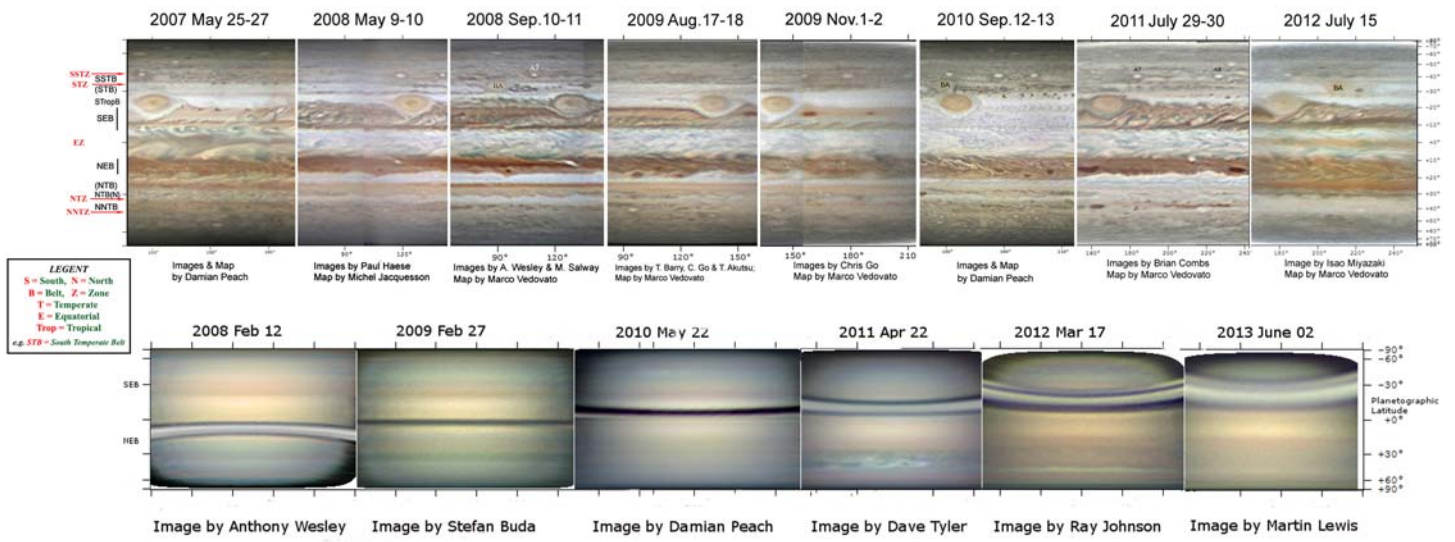


Figure 2. *Top:* Changes in Jupiter’s belts, 2007–2012, in visible colour maps. Cylindrical projection maps made in *WinJUPOS* are aligned to show the changing latitudes of the edges of the belts. Abbreviations for the major belts are labelled at left. The figure depicts well the major changes in belts and zones from year to year, including South Equatorial Belt (SEB) fading and revival in 2009–2011, and North Equatorial Belt (NEB) narrowing and revival in 2011–2012.¹¹ *Bottom:* Changes in Saturn’s belts from 2009 to 2013 are shown in these cylindrical projection maps made in *WinJUPOS* and derived from colour images (Differences between images in overall colour balance are largely due to different processing by individual observers). These maps are aligned to show the changes in latitudes of the edges of the belts plus major changes in the belts over this period. In particular, the maps show the fading of the NEB during 2010 and the appearance of the Great White Storm in the northern hemisphere during 2010–’11. The maps also show the varying aspect of projection of both the rings and the ring shadow onto the planet resulting from the varying inclination of the rings with respect to the Earth. Map by co-author M. Foulkes. (South is up for both planets).

observations; and tracking of features and alerts of new events which are worthy of professional study. Therefore, the key advantage that the amateur community provides is that of flexibility and spatiotemporal coverage for context. Both of these widen the discovery space significantly compared to the capabilities of professional observers.

This paper is structured as follows: Section 2 describes professional–amateur (Pro–Am) collaborations currently under way regarding Jupiter and Saturn. Information on the digital observations methodology is provided in Section 2.1 along with the online databases where they are stored. In Section 2.2 Pro–Am collaborations and results regarding the atmospheric features of Jupiter and Saturn are discussed, while in Section 2.3 the support of space missions by amateur imaging is highlighted. The investigation of impacts on Jupiter’s atmosphere is presented in Section 2.4. Stellar occultations as atmospheric probes are discussed in Section 2.5. Section 3 summarises and concludes the current paper.

2. Fields of Pro–Am collaboration

2.1 Systematic multi-wavelength observations and databases

Amateurs observe Jupiter and Saturn with a variety of telescopes, mostly with apertures between 15–40 cm. Since the early years of the 21st century, amateur work has mostly consisted of imaging with webcams combined with processing by software to select and combine the sharpest images. This technique has been

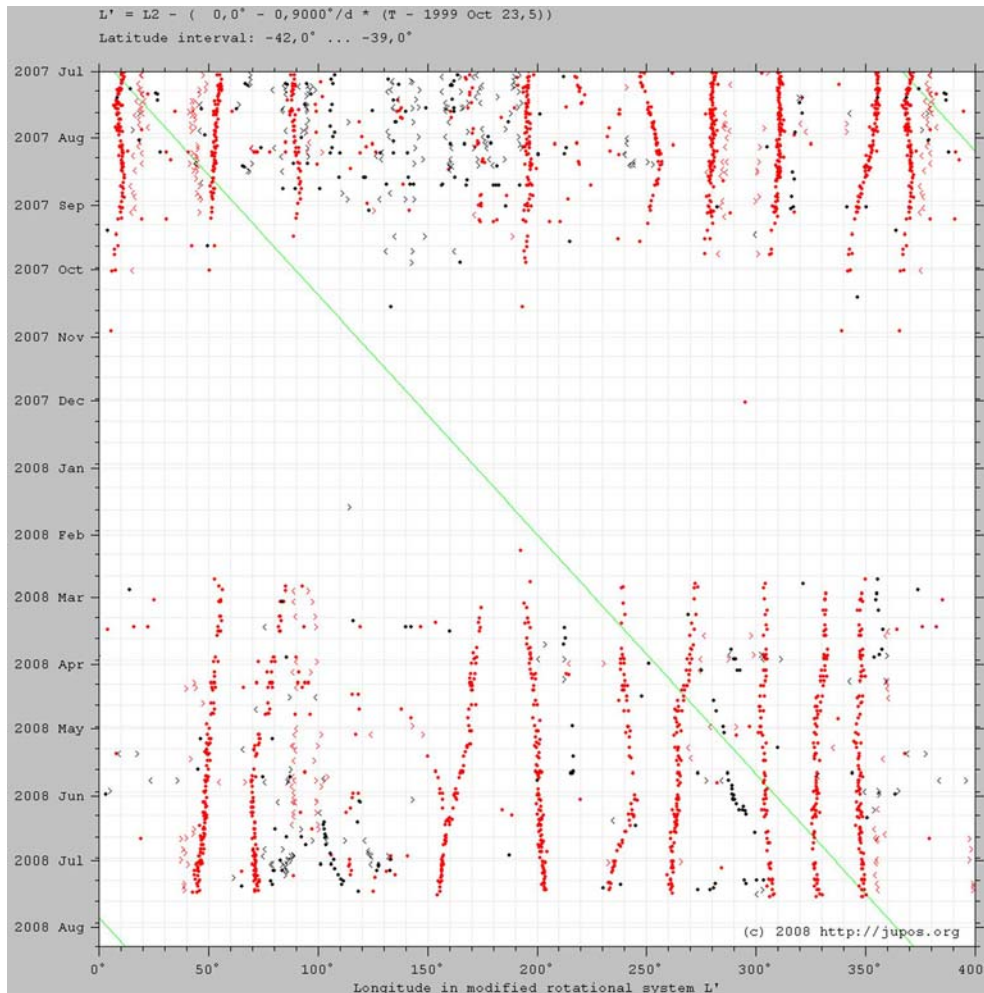


Figure 3. Tracking of white ovals (shown as red dots) and dark spots (shown as dark dots) in SSBT/SSTZ (see Figure 2) in 2007–2008 by the JUPOS team. Every dot is a position measurement of a feature. Dense and continuous observations are required to track in detail the motion and drift rate (speed) of meteorological formations. In this chart, the longitude scale is chosen to move at exactly 0.9°/day relative to System II, thus approximately matching the mean drift of the long-lived features. The green line is the longitude 0° of System II, which is oblique as the graph is made with a modified rotation system L’ defined in the header of the graph. JUPOS can also produce charts in System III, but System III is not used routinely because it is repeatedly changed by the International Astronomical Union, whereas System II has been precisely defined for over 100 years and approximately matches the mean drift of the Great Red Spot.

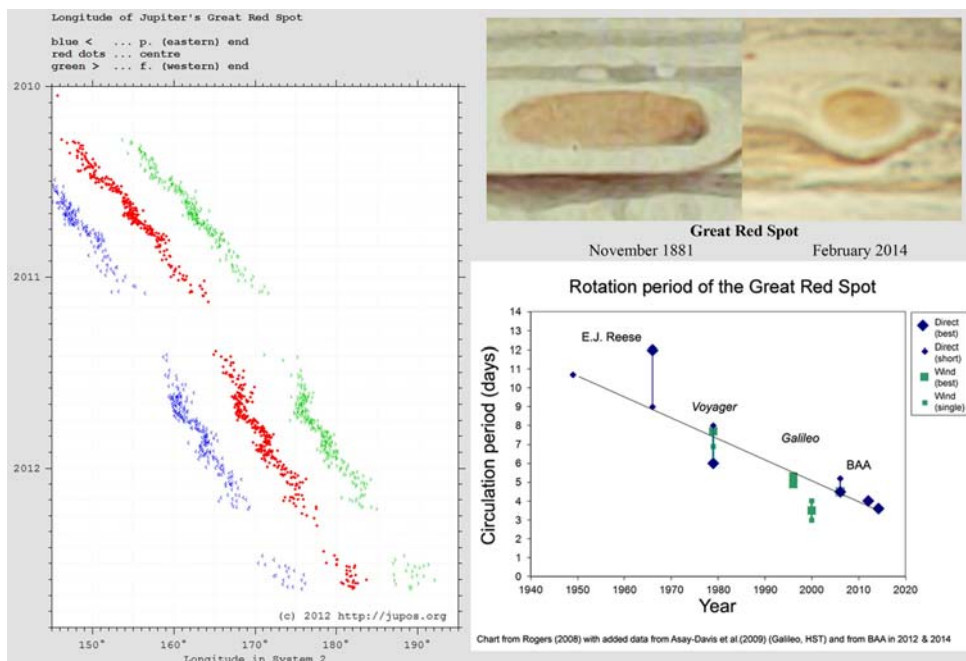


Figure 4 (left). Properties of the Great Red Spot (GRS), the largest vortex in Jupiter, which has a variable reddish colour. Amateur contributions to the study of this vortex have been extensive. **A) Left panel:** A drift chart of the GRS by the JUPOS team. In this graph we can see part of its long-term historical drift rate and length variation, together with its 90-day zonal oscillation. **B) Top right panel:** Comparison of the size and colour of Jupiter’s Great Red Spot as drawn by Thomas Gwyn Elger on 1881 November 28, (BAA archives) and as imaged by co-author E. Kardasis 133 years later, on 2014 Feb 27 (South is up). The length was 34° (39,600 km) in 1881 and 13.7° (16,000 km) in 2014. **C) Bottom right panel:** Chart showing the shortening of the GRS internal rotation period from spacecraft and ground based amateur observations, by co-author J. H. Rogers.¹⁸ This has been updated to 2014 January, when amateur observations showed that the GRS was smaller than ever before and its internal rotation period had also shortened.¹⁷ Acting on this information, a professional team obtained images with *HST* at short notice to investigate the changing dynamics of the GRS.¹⁹

referred to as ‘lucky imaging’¹ but we do not use this term, as good results require technology, skill, and perseverance, just as much as luck. In recent years cameras based on the advantages of webcam technology have been designed for digital planetary observations (planetary cameras). These cameras capture videos over several minutes, producing hundreds of images in a rate of 15 to 200 frames per second. Software such as Registax⁷ or Autostakkert⁸ is then used to select the images with the highest-spatial-frequency components, to align and stack them. Further image processing (e.g. applying wavelets, adjusting brightness–contrast) is then performed in these or other photo-processing programmes.

Normally the images have to be taken within a span of ~2–3 minutes for Jupiter (~4 minutes for Saturn), to avoid smearing by the planet’s rotation. However, a recent innovation in the *WinJUPOS*

software suite allows either raw images or stacked images to be ‘derotated’ to compensate for the planet’s rotation, allowing much longer integrations which produce substantially sharper images, especially in mediocre seeing. All this image processing does not preserve absolute intensity values, but it allows a great deal of fine detail to be resolved, and independent imaging and processing by different observers confirms that relative intensities and colours can be realistically, if qualitatively, portrayed.

Images can be taken in monochrome or in colour. While some observers use colour planetary cameras, most use monochrome planetary cameras with a series of colour filters. The most common filters used by amateurs are the red (R ~580–670nm), green (G ~500–580nm) and blue (B ~390–500nm) filters supplied by various companies, the synthesis of which results in colour images.

(However, at present amateurs do not have any way of recording absolute colours; colour balance in images is arbitrary, and chosen generally for best contrast rather than for reproducing the true predominantly yellowish colours of Jupiter and Saturn).

Additionally, near-infrared (IR) filters are used (~680–900nm), providing continuum images which penetrate slightly deeper into the clouds, and most importantly the narrow-band CH₄ filter (890nm, with typical Full Width at Half Maximum of 5–18 nm depending on manufacturer) that shows light reflected from the highest clouds. A near-ultraviolet (UV) filter may also be used (<390 or <360 nm) (Figure 1). For Saturn, the >610nm band-pass filter (far red plus near-IR continuum) is very useful for detecting discrete atmospheric spots.

The need for international databases to host this vast number of worldwide observations is fulfilled primarily in two sites: the professional International Outer Planet

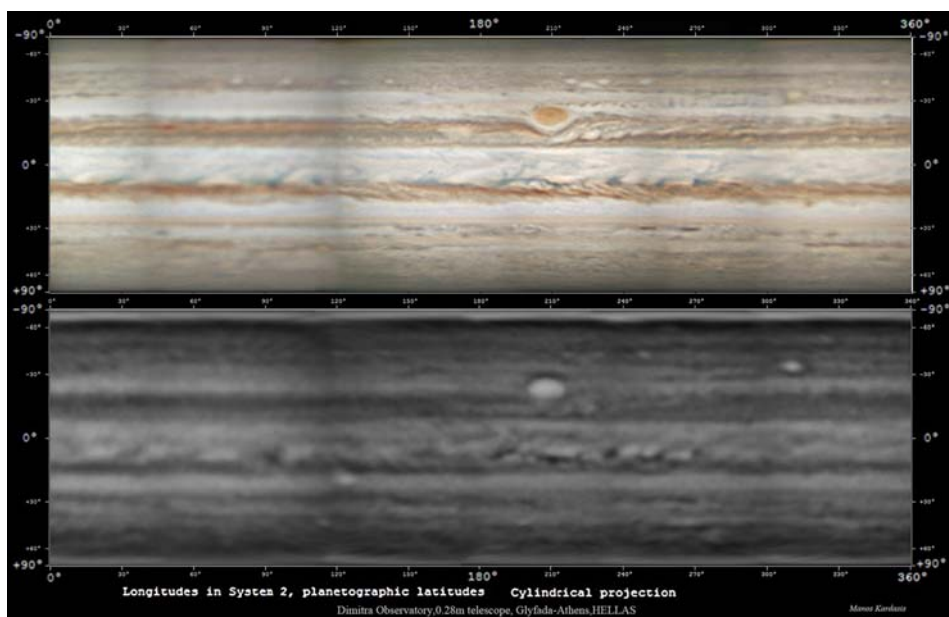


Figure 5. Map of Jupiter during 2014 March 14–15, made from individual observations of the planet with the use of *WinJupos* software. **Top:** Map at visual wavelengths with RGB filters. **Bottom:** Map with a methane CH₄ 890nm filter which reveals information on cloud altitude (brighter areas are higher-altitude formations). Observations near opposition, by a single dedicated amateur can cover a wide swath of longitudes to create a map. (Images and map by co-author E. Kardasis.²⁰ South is up).

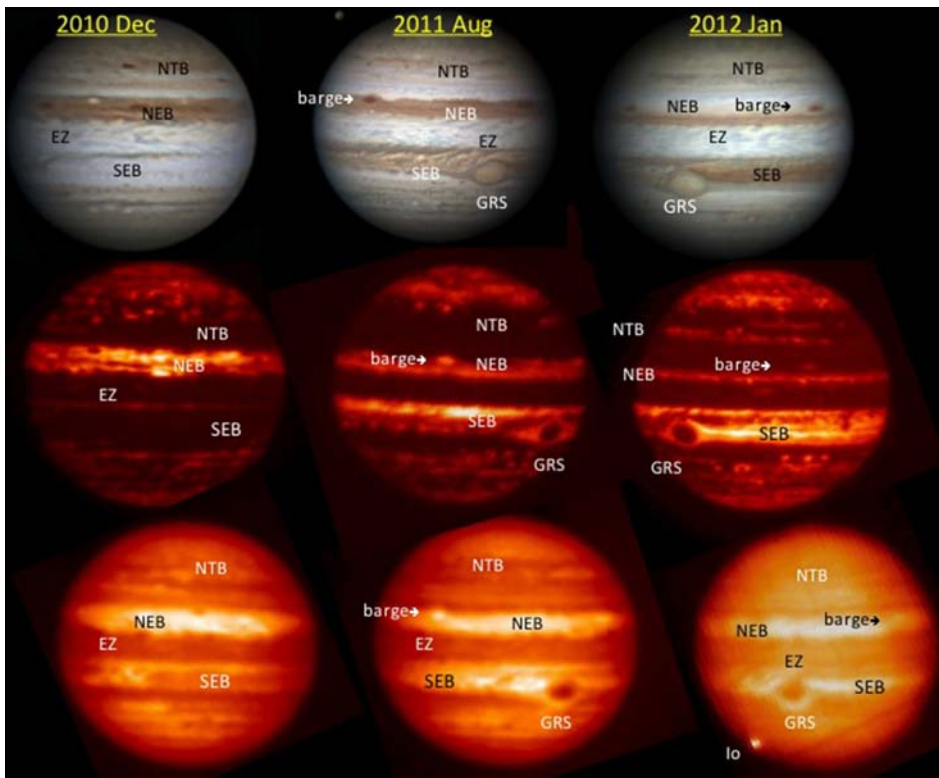


Figure 6. Amateur RGB images (*top*) and professional thermal-infrared images (*middle and bottom*) during phases of the SEB revival and subsequent NEB fade. The middle images are taken with a filter centered at 4.78 microns, in the ‘5-micron spectral window’, showing thermal radiation from deep levels with clouds silhouetted dark against it, sensitive to cloud all the way down to the 2–3 bar pressure levels. The lower images are at 8.7 microns, in an atmospheric spectral window between methane emission and ammonia absorption lines that is not quite so transparent and only sees down to the ~1 bar level; so it may be sensitive only to clouds at the ammonia condensation level, and nothing deeper. (All images with North up).

Watch–Planetary Virtual Observatory and Laboratory database (IOPW–PVOL database)⁹ and the amateur ALPO–Japan database.⁵ A dedicated database of the position of features from historical and current observations is provided by the JUPOS project (Database for Object Positions on Jupiter) which can be accessed at ref.10. Moreover, *WinJUPOS*¹⁰ is an important planetary software suite developed by Grisca Hahn, enabling amateurs to perform sophisticated analysis of images. Among the various applications it enables construction of global maps, measurement of positions of cloud features, their analysis in drift charts, and examination of their motion in time. Such drift charts are becoming increasingly important to guide professional observations, whether from observatories or from spacecraft, as we discuss below.

2.2 Examination of the variability of cloud features

The ever-changing atmospheres of Jupiter and Saturn, with a large number of atmospheric features (especially Jupiter), need continuous long-term coverage. Moreover, the fast rotation of Jupiter (~9h 55m) and Saturn (~10h 39m) requires a broad geographic distribution of observers around the world to maximise the coverage of events. Large-scale climatic cycles occur at intervals of several years (Figure 2). The onset of these cycles is usually unpredictable, and when they do begin, time availability on professional telescopes is not enough to follow them, thus only amateurs can offer continuous observations over many years. On the other hand, only professionals can observe in mid-IR to detect features below the visible cloud-tops, to do precise high-resolution photometry to retrieve cloud

structures, and (using spacecraft missions) to resolve cloud textures sufficiently to provide accurate wind profiles over the whole planet. Atmospheric scientists aim for a synthesis of all these observations, complemented by theoretical and computational modelling, to understand the atmospheres of these planets.

2.2.1 Evolution of the atmosphere of Jupiter

Amateur studies

For Jupiter, more than any other planet, there has been a long history of important amateur research, thanks to the fortuitous fact that most of the planet’s major atmospheric features are clearly visible and resolved in moderate-sized amateur telescopes. It was amateurs in the 19th and early 20th century who identified all the regular currents governing the motions of large weather systems in different latitudes; who discovered several of the major jets; and who described recurrent climatic cycles such as the ‘fading’ and ‘revival’ of the SEB. Amateurs continued to monitor these features throughout all subsequent years, publishing a continuous record of the visible atmospheric features (summarised in refs. 12 & 13). This work has continued to the present day, now amplified by the use of modern imaging techniques, with a worldwide network of proficient observers, and modern analysis techniques developed by the JUPOS project.¹⁰

JUPOS is a project of an amateur team in Europe, led by Hans-Jörg Mettig, that uses amateur observations and the *WinJUPOS* software to track the evolution of Jupiter. Measurements of the positions (longitude/latitude) of all features clearly visible on the image are made, and recorded in a database. The database is first used to produce drift charts, which display the movements of the spots against time for a given latitude span (Figure 3) or a particular object (Figure 4A). Second, the graphs allow the computation of the drift rate of each spot against a rotation system, and changes of speed in relation to morphology can be tracked. It is now possible even to calculate the global zonal wind profile.^{14,15,16}

Finally, using *WinJUPOS*, images obtained in a time span of no more than 2–3 days can produce a map of Jupiter showing the global aspect of the planet on a given date (Figure 5). A longer time span would give an inconsistent image of the planet because of: (i) the difference of rotation periods between equatorial and other latitudes, and (ii) the rapid evolution of some features in very active regions.

The results are used by the JUPOS team with co-author J. H. Rogers to make systematic reports of the planet’s atmosphere.¹⁷ These provide detailed descriptions of the phenomena with compilations of world-wide amateur images, in order to maintain a continuous record of atmospheric evolution, report new phenomena that are worthy of professional investigation, provide predictions of the locations of features, and estimate the likely outcomes of ongoing disturbances.

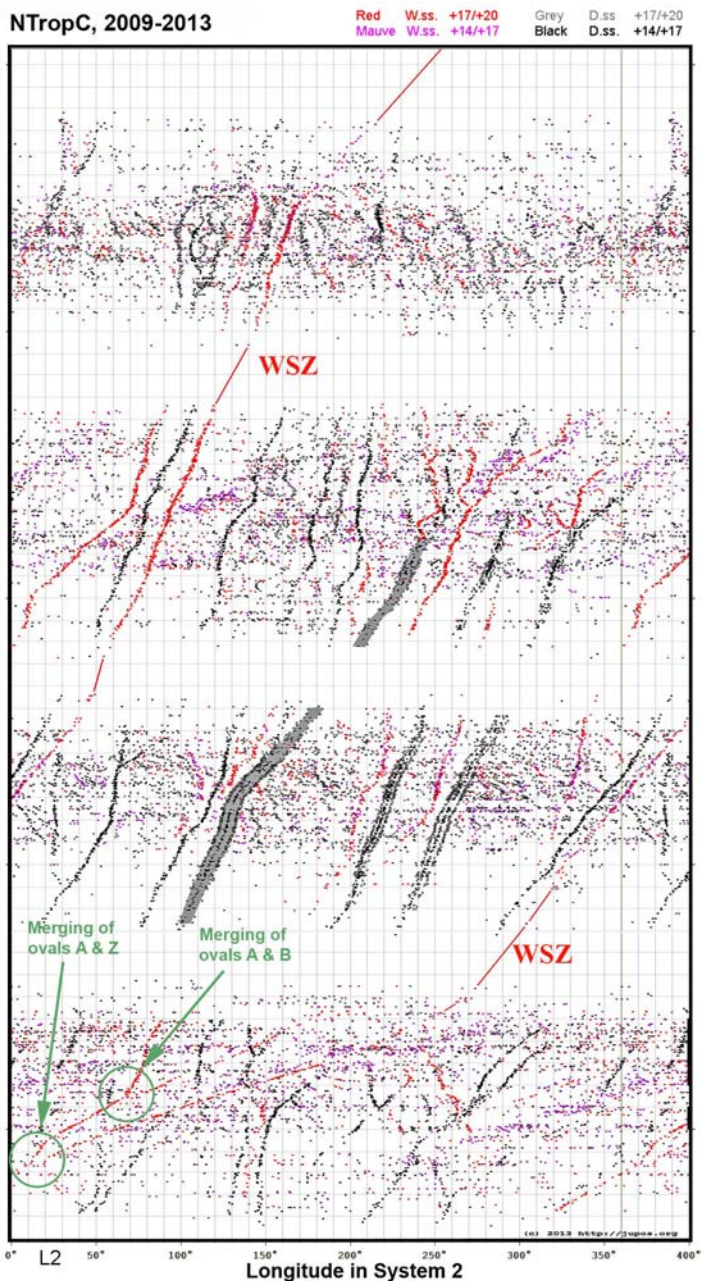


Figure 7. A JUPOS drift chart for the North Tropical domain, for 2009–2013 (in L2; a latitude key is given at the top). The track of White Spot Z (WSZ) is marked in red. The merging of ovals A and B is marked (upper right green circle). The merged oval A/B (referred as A) a few weeks later merged with WSZ (lower left green circle). We can also see the tracking of other persistent bright and dark ovals. (Adapted from ref.39.)

Pro-Am collaborations

At present, the relationship between amateur work and professional science can be summarised in three categories:

1) Amateur contributions in planetary imaging and analysis

As mentioned already in the Introduction there are several available databases which archive amateur images.^{3–6,9} These have served as repositories of valuable data which are used by both the amateur and professional communities to investigate atmospheric phenomena, leading to important Pro-Am collaborations and peer-reviewed publications (e.g. the GRS shortening presented in Figure 4¹⁹ or the SEB revival cycle;²¹ more are discussed in the next sections). The Planetary Sciences Group UPV/EHU²² led by Agustin Sanchez-Lavega has published works based largely on amateur images since about 1990, with leading amateurs as co-authors (e.g. refs. 16, 23, 24). They continue to publish many papers that combine feature tracking from images with physical analysis and dy-

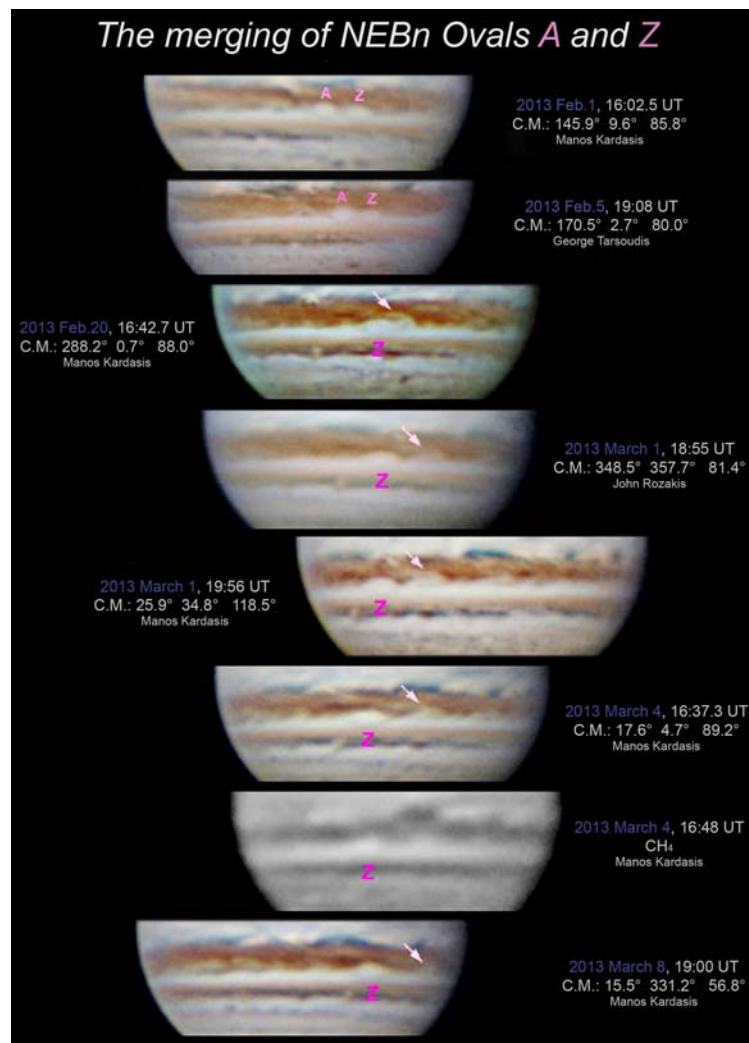


Figure 8. Interaction of NEBn ovals A&Z at 16° North in early 2013 (Greek observations as part of a compilation in a BAA Jupiter Section report;⁴⁰ South is up.) WS-A and WS-Z interacted between February 10–19. As in previous such encounters WS-A squeezed round the South side of WS-Z and was pulled into a loop; part of it probably merged with WS-Z, while the other part moved to the following side for more than two weeks (pink arrow).

namical modelling. The group also operates the IOPW amateur network database⁹ for which the software tool *PVOL* has been developed. *PVOL* helps in finding and selecting the planetary observations taken by amateur astronomers.

2) Alerts

Amateurs can alert professionals to new atmospheric features or events, or predict the positions of features of interest. These alerts sometimes prompt professionals to target infrared telescopes or spacecraft (*Galileo*, *HST*, *New Horizons*).

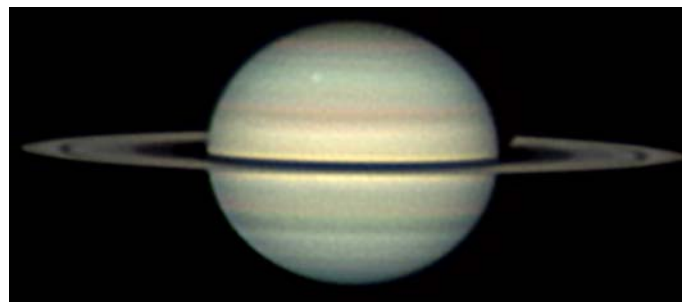


Figure 9. Colour image taken by Stefan Buda showing a bright storm, preceding the Central Meridian (2009 April.12, 11:02UT, South up).

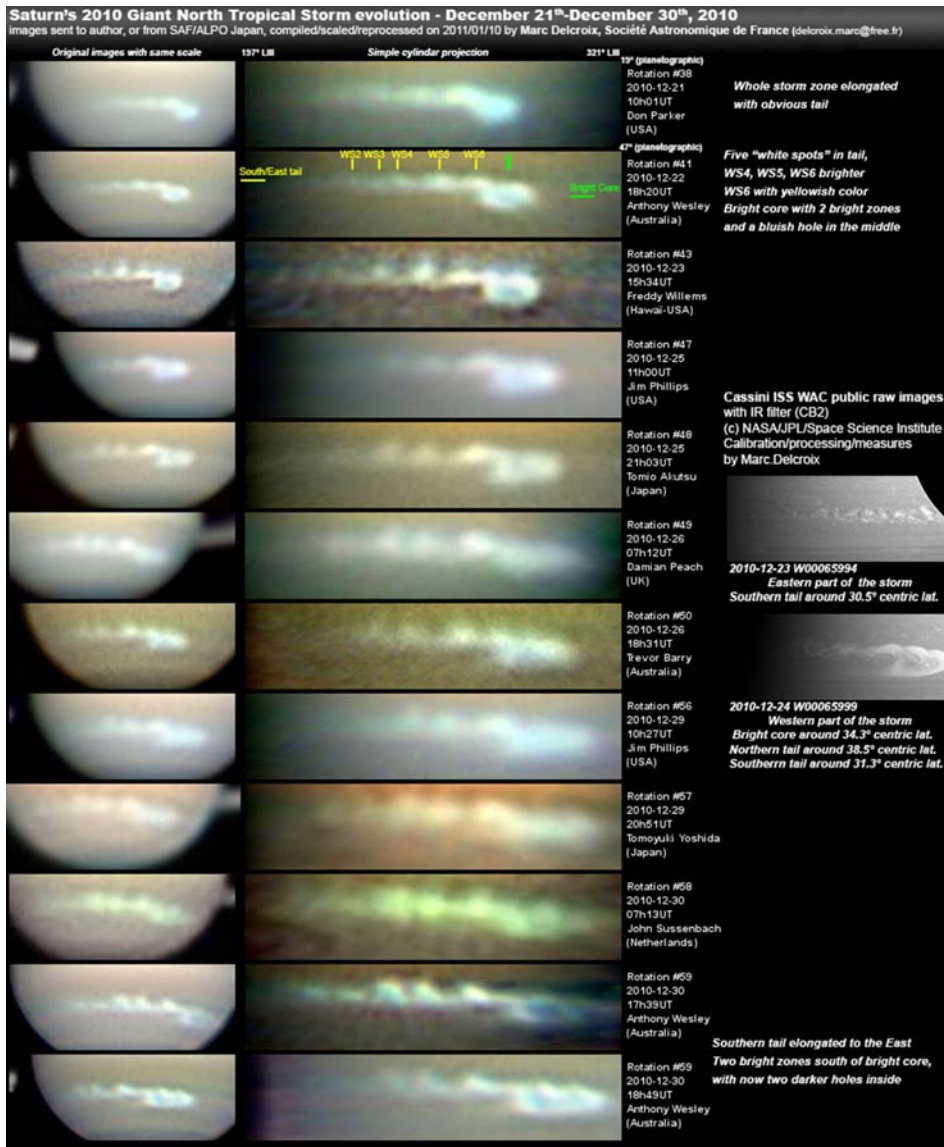


Figure 10a. Evolution of Saturn's growing Great White Spot in 2010–11 from amateur images to scale (left), maps made from the amateur images (centre) and images by the Cassini spacecraft (right).

Measures* (centric lat.) from Dec. 8th to Jan. 1st

Bright core:	33.9° lat. ; LIII drift rate: +2.29°/day
WS6:	30.0° lat. ; LIII drift rate: +1.11°/day
WS5:	29.8° lat. ; LIII drift rate: +0.54°/day
WS4:	29.4° lat. ; LIII drift rate: +0.38°/day
WS3:	29.1° lat. ; LIII drift rate: -1.11°/day
WS2:	29.6° lat. ; LIII drift rate: -0.94°/day

Size* extension from Dec. 22nd (rotation #41) to Dec. 30th (rotation #49)
 Core: Latitude stable ~9.8° centric, 9 500 km. Longitude 17° to 31° (15 000 to 28 000 km)
 Tail: Longitude from 47° to 71° (44 000 to 67 000 km)
 Whole: Longitude from 61° to 101° (57 000 to 96 000 km)

*: indicative measures with WinJupos - affected by filters used and length of acquisition time

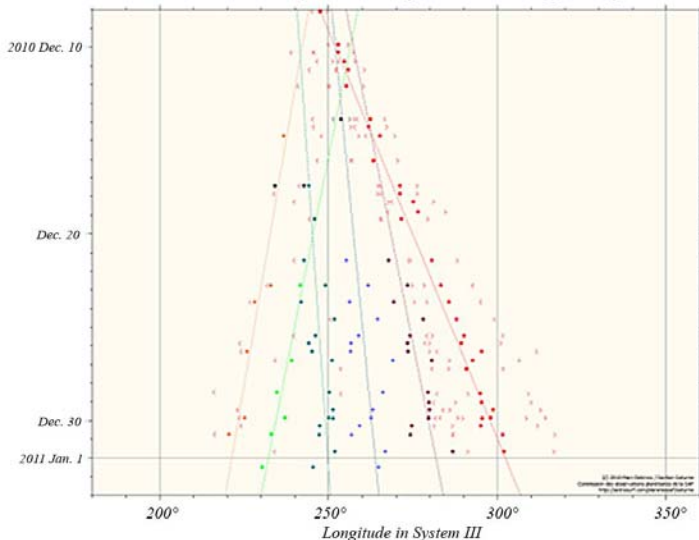


Figure 10b (right). Tracking of white spots on Saturn. Every dot is a position measurement of a spot used to track in detail their motion and drift rate (speed). Analysis by co-author M. Delcroix from selected amateur and Cassini images (South up).

3) Complementary support for space missions

Amateurs can provide information at visible wavelengths to supplement professional observations at infrared wavelengths,²⁵ or 'snapshots' taken by spacecraft. The complementarity of these data sets was well shown during the Cassini flyby of Jupiter in 2000/01²⁶ and subsequently. Thus, amateur reports can provide context on timescales of days (for matching actual features), months/years (for describing a climatic cycle that may be under way), and years/decades (for understanding the historical pattern of such processes).

Jovian atmospheric features subject to Pro-Am collaborations

Phenomena of joint interest include the permanent jets, major planetary-scale disturbances, vortices, waves, other disturbances, and ephemeral events such as impacts. The jets constitute the fundamental framework of Jupiter's atmosphere, but until recently only spacecraft were capable of observing their full detail. Nowadays, amateur observations can sometimes reveal the peak speeds of the major jets, and previously unknown variations within them (North Equatorial Belt-NEB,¹⁴ North Temperate Belt south-NTBs,²⁷ South Equatorial Belt north-SEBn²⁸).

Wave phenomena on the major equatorial jets are of particular interest and recent papers have been able to combine amateur and professional observations and analysis to produce informative synthesis which would not have been possible with either data set alone, for example on thermal waves on the NEB²⁶ and dynamical waves in the SEBn jet.^{28,29}

The most impressive transient phenomena include wholesale fading or narrowing and subsequent violent revivals of the South Equatorial Belt (SEB), North Temperate Belt (NTB), and North Equatorial Belt (NEB).^{13,21–24,30,31} After many years with no such disturbances, these have recently resumed, with SEB revivals in 2007 and 2010, NTB revivals in 2007 and 2012, and an NEB revival in 2012 (all reported in detail on the BAA web site;^{17,31} see also Figures 2 & 6). Early Pro-Am studies of some of these have been published.^{21,32,33} Historically these disturbances have appeared to be dissimilar, with the violent disturbances being initiated by the appearance of an intense local storm in the SEB, or a very fast-moving plume on the NTB jet (on the south edge of the belt), or more extended disturbances in the NEB. However, recent Pro and Am studies have converged to reveal that each of these outbreaks has a similar convective origin.^{30,32} A continuing mystery is why the SEB and NTB cycles often occur within a year of each other, along with striking colouration in the equatorial zone, comprising a 'global upheaval'.^{13,17}

Vortices, most prominently anticyclonic ovals, are also followed

Figure 10b (left). Tracking of white spots on Saturn. Every dot is a position measurement of a spot used to track in detail their motion and drift rate (speed). Analysis by co-author M. Delcroix from selected amateur and Cassini images (South up).

from their generation through evolution in shape, colour and speed. The largest of these is the Great Red Spot (GRS), which has been observed by amateurs since 1831 if not earlier.¹³ Over that period it has shrunk by 50% of its original size (Figure 4B), has interacted with numerous other features and spots, and has changed its drift rate. Furthermore, in recent decades its internal rotation period has shortened (Figure 4C).¹⁸ Nevertheless it has consistently maintained an oscillation in longitude with a 90-day period (Figure 4A).^{18,34,35}

Other long-lived white ovals include a well-defined series in the South South Temperate Zone (SSTZ), whose changing motion during 2007–'08 can be seen in Figure 3. Recently, JUPOS analysis has revealed that anticyclonic ovals in the North North Temperate Zone (NNTZ) can also be tracked over several years, in spite of large changes in drift rate, and that one is a very long-lived Little Red Spot.³⁶ In the South Temperate Zone (STZ), amateurs monitored long-lived white ovals that merged in 1998–2000 to form the single large oval BA, and reported that BA turned red in 2006; this discovery by Christopher Go triggered much professional interest.^{37,38} JUPOS data have revealed how its motion is affected by South Temperate Belt (STB) segments impinging on it.¹⁵ Amateurs have likewise tracked a long-lived white oval in the North Tropical Zone, 'White Spot Z (WSZ)' (Figure 7)³⁹ which also merged with another oval in 2013 (Figure 8),⁴⁰ and subsequently turned pale reddish as well.³⁹ These interactions of anticyclonic vortices are providing rare probes of the atmospheric dynamics and of the chemistry which generates red colour on Jupiter.



Figure 11a. Colour image of Saturn by Trevor Barry showing the dark northern hemisphere vortex approaching the central meridian (2013 Feb 15, 18:11 UT, South up).

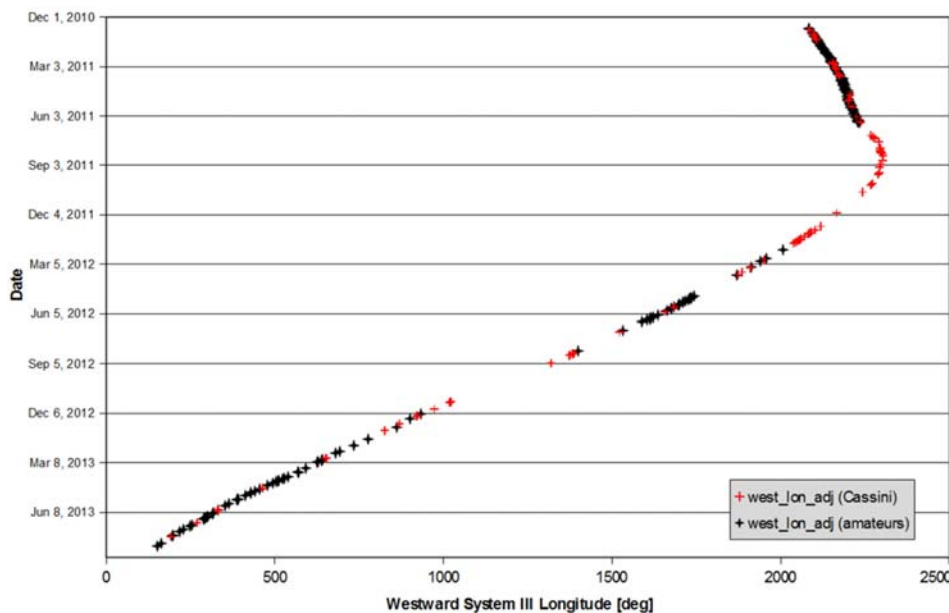


Figure 11b. Tracking of GWS dark oval longitude since the 2010 GWS; complementary coverage by amateur data (black) and *Cassini* data (red).⁵²

2.2.2 Evolution of the atmosphere of Saturn

For Saturn, like Jupiter, much of the historical record of atmospheric cycles has come from amateurs, including progressive variations of the belt patterns around the saturnian year (Figure 2, bottom), and the rare 'Great White Spot' (GWS) storms which have been observed roughly once per saturnian year.⁴¹ The GWS of 1990 was discovered by amateurs and soon observed by professionals and by the *HST*.^{42,43}

Since the *Cassini* spacecraft arrival in 2004, a fruitful Pro–Am collaboration on the planet's atmosphere study has developed. The spacecraft's Radio and Plasma Wave Science instrument (RPWS) regularly observes Saturn Electrostatic Discharges (SEDs), radio signatures of lightning. As these observations lack resolution, amateurs' images at visible wavelengths help to locate the white spots (thunderstorms) that are the sources of these SEDs (Figure 9).⁴⁴ Furthermore, given the increasing quality and coverage of these images over the years, amateurs through their own analysis can calculate the drift rates and follow the morphological evolution of the visible white spots, even the smaller ones.⁴⁵

When the new Great White Spot (GWS) erupted in 2010 December,^{46,47} it was independently discovered by the *Cassini* RPWS team (Dec 5) and by the amateur Sadegh Ghomizadeh (Iran, Dec 8); its first appearance was then identified on images taken on Dec 5 by *Cassini* and by the amateur Toshihiko Ikemura (Japan). *Cassini*

was then instructed to take high-resolution multispectral images starting several weeks later, while amateurs monitored the storm's phenomenal growth in the meantime. Hence, amateurs could fully participate in the scientific study of this rare and major event (see Figure 10). They were fully involved in the studies from the beginning of this storm till its end.^{46–51} Their work on the analysis of approximately 100 spots contributed to the study of Saturn's wind profile over the latitude range of the GWS.⁴⁷

As the storm decayed, a large dark vortex appeared in the same latitude band, which attracted professional interest.⁵⁰ This has been imaged by the *Cassini* spacecraft and the results are presented in ref. 52. It has also been imaged and tracked by amateurs (Figure 11). This spot is one of the longest-lived features ever recorded on Saturn.

In 1980–'1 the Voyager spacecraft observed for the first time a strange, hexagon-shaped structure in the upper clouds of Saturn's north pole.⁵⁴ The hexagon seemed to have almost-stationary motion in the System III rotation period. More recently, amateurs using the latest imaging techniques have been able to detect the hexagon (Figure 12). A Pro–Am collaboration with detailed observations from various geographical locations confirmed the hexagon configuration and determined that its movement remains extremely stable and may be linked with deeper layers of the planet,⁵⁵ although its movement is non-zero relative to Saturn's System III longitudes. Such observations made over a long period of time will

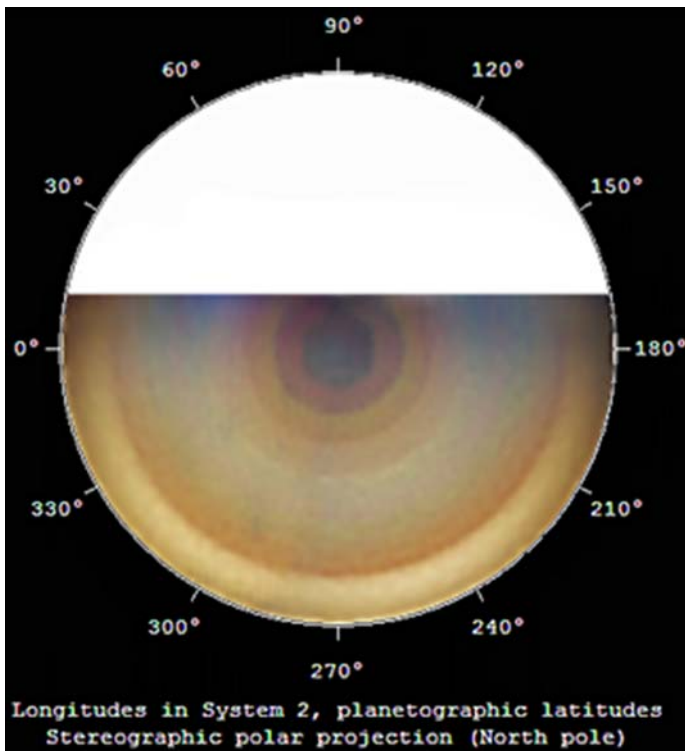


Figure 12. North polar projection map of Saturn showing the North Polar Hexagon (dark grey, at centre). Map generated by Darryl Milika & Pat Nicholas using *WinJUPOS*, from their RGB images taken on 2014 Feb 16.

allow the rotation period of the hexagon to be established plus any long term changes identified, even after the *Cassini* mission ends.

2.3 Ground-based space mission support

The importance of Pro-Am collaborations is also evident in the support of spacecraft missions, like the *Galileo* and *Cassini* outer-planet missions to Jupiter and Saturn, respectively. *Galileo* suffered from a failure of its high-gain antenna to deploy properly and its science team had to contend with an extremely reduced data rate. *Galileo*'s Atmospheric Working Group decided to develop the best science via 'campaigns', in which specific features would be targeted and viewed by all the remote-sensing instruments at the same time, from the ultraviolet through the thermal infrared. Although some targets were belts or zones, not confined in longitude, most were discrete features.

Pointing for these campaigns needed to be developed months ahead of time and loaded into the spacecraft memory, and it was important to understand the drift rate of the features in order to make good predictions of their location at the scheduled time of the observations. Although some of this work was aided by a program that routinely tracked features using a suite of near-infrared wavelengths from NASA's IRTF atop Mauna Kea, Hawaii, other features were not clear in the near

infrared. For that purpose, the mission relied on observations from amateurs. Amateur observations were also used to verify the results from the NASA IRTF program.⁵⁶

The operations of the *Cassini* spacecraft were not so difficult and routine observations were and are still being made by many instruments. Nevertheless, amateur observations of Saturn have played key roles. Because *Cassini*'s remote-sensing instruments cannot point everywhere at the same time, it falls to the amateur community to inform the *Cassini* science team about rapidly evolving features in Saturn's atmosphere. A very good example, already described above, occurred at the very beginning of the great northern hemisphere storm of 2010–'11. In that case *Cassini*'s detection of an intense radio burst coincided with amateur detection of a new bright cloud, which marked the initial upwelling of this giant thunderstorm. Remnants of that storm are still being tracked by both professional and amateur astronomers (see section 2.2.2).

The science team for the *Juno* mission will be soliciting Earth-based observations during its remote-sensing orbits in 2016–'17 to provide contextual spatial information to supplement its narrow coverage of the planet in each orbit, as well as temporal coverage that is relevant to the evolution of the features that will be observed.⁵⁷ Co-author G. Orton will be serving as the point of contact.

Amateur astronomers can benefit the *Juno* mission directly via the Mission Juno / JunoCam website (<https://www.missionjuno.swri.edu/junocam>), linking to the 'Planning' section. This site provides an opportunity for continuous updates to a database of high-quality amateur (and some professional) images of Jupiter from 2015 onwards, as well as a forum for discussing the features shown in the images. A similar involvement of amateurs is foreseen for the European Space Agency's JUICE mission in the timeframe of the 2030s.⁵⁸

2.4 Investigation of impacts on Jupiter's atmosphere

Since the 1994 impacts of the fragments of comet Shoemaker-Levy 9, comprehensively observed by both professionals and amateurs, amateur observations of Jupiter have resulted in the discovery of the dark visible trace of an impact in 2009, and three fireballs in its atmosphere produced by the impacts of smaller objects. The impact cloud discovered by Anthony Wesley on 2009 July 19 was immediately followed up by professionals using infrared observatories and *HST*. The fireballs were detected on 2010 June 3, 2010 August 20 and 2012 September 10, and the first of these was also followed up by professionals using infrared observatories and *HST*,⁵⁹ although no residual trace of the impact could be detected. While the size of the object which left a trace in 2009 is estimated to have been between 200 and 500m, the later fireballs were in the category of 5–20m in size, comparable to the recent Chelyabinsk airburst.⁶⁰

There could be more impacts still undetected on stored amateur videos.

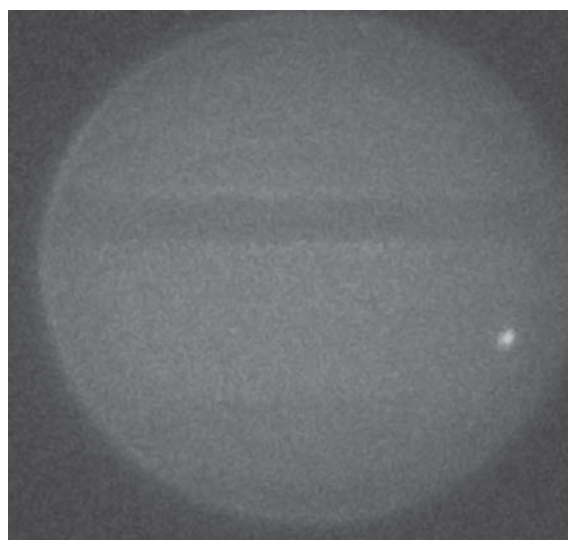


Figure 13. A detection image generated by *DeTeCt* software (image with maximum value minus mean value for each aligned pixel) from an acquisition from Christopher Go on 2010 June 3, of a real detected impact.⁶⁰ (South up).

Hence, a project was developed called DeTeCt with software and database to search for fireballs on existing videos (Figure 13), in order to constrain the rate of detectable Jovian impacts.^{61,62} As of the final editing of this paper (2015 December), more than 41.8 days' total time of videos (from 41,535 videos from 45 observers acquired between 2004 February and 2015 November) were analysed. The lack of positive detections in this preliminary dataset merely suggests that the observable Jovian impact rate is no more than 9 per year. Further data will provide a more accurate impact rate, which will be valuable in various fields of research (*e.g.* dating the surfaces of the Galilean moons, and better estimation of the small-body population in the outer solar system). Consequently, there is no doubt that Pro-Am collaborations contribute actively to the scientific study of the impacts on Jupiter.^{59,61}

A similar project has been launched in 2014 for detecting fireballs on Saturn.

2.5 Stellar occultations as atmospheric probes

The structure and variability of the upper atmospheres of the giant planets may be investigated by occultation techniques.⁶³ When a spacecraft is near the planet, its radio signal may be monitored from the ground as it disappears and reappears behind the planet.^{64,65} The spacecraft itself may be used as an observation platform to monitor *e.g.* the attenuation of a star's flux in the UV due to absorption.^{66,67}

In contrast, ground-based photometric monitoring of stellar occultations measures the attenuation of starlight by the planet's intervening atmosphere due to differential refraction. It is complementary to the other techniques because it samples a different pressure

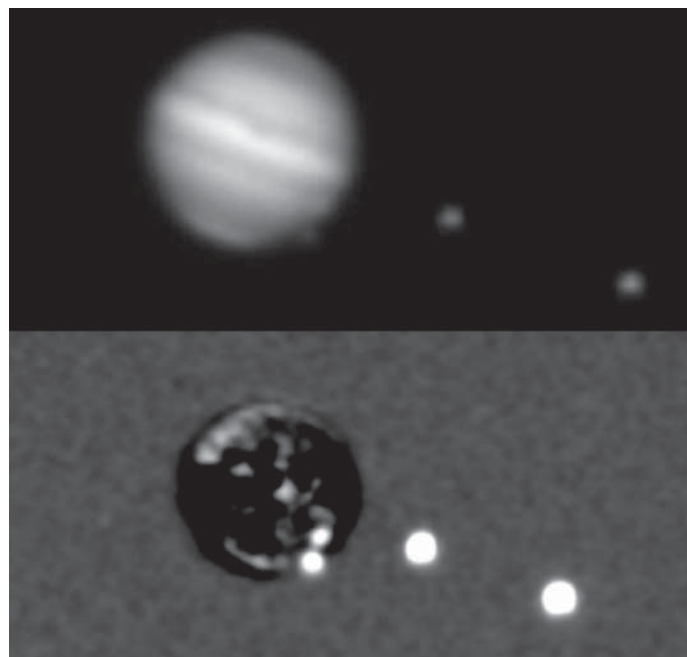


Figure 14. Sample frame of the occultation of 45 Cap by Jupiter on 2009 August 3/4. The frame is from a series obtained with a 0.5m instrument at Sabadell observatory in Spain (Minor Planet Center observatory code 619) in the 0.89 μm methane band before (*top*) and after (*bottom*) subtraction of a template of Jupiter. The star 45 Cap can be seen impinging on Jupiter's disk near the 5 o'clock position. The bright sources to the right of Jupiter are the moons Io and Europa (North up).

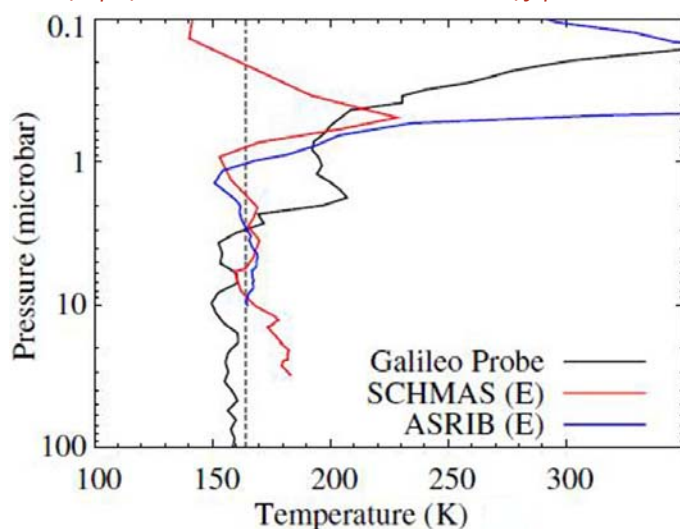


Figure 15. Atmospheric profiles at ingress compared with *in situ* data from the *Galileo* Probe ASI investigation (black curve). The dotted vertical line indicates a calculated weighted mean value of the isothermal solutions obtained from the analysis (see ref.67 for details). Abbreviations are as follows: BATH: 0.5m, Hakos, Namibia; SCHMAS: 1.52m, Teide, Canary Is.

regime (1–100 microbars) than the other two methods (radio: 1–1000 millibars; UV: <1 microbar). This requires a sufficiently bright star to act as source and such opportunities are not frequent.

A recent example was the occultation of the bright star 45 Capricorni ($V=5.5$ mag) by Jupiter on the night of 2009 August 3–4. Its occurrence during the summer motivated a Pro-Am campaign to observe it.^{68,69} In this sense, this undertaking was different than previous campaigns^{70–77} in that it featured strong participation by amateur astronomers equipped with 0.4m-class instruments. To minimise the contribution of Jupiter's atmosphere to the stellar flux, observations took advantage of deep absorption bands in Jupiter's spectrum in the 0.89- μm methane band (Figure 14).

The occultation was successfully recorded from 9 different locations in Namibia, Greece, Brazil and Spain. Full details of the observations, data reduction and scientific analysis may be found in Christou *et al.*⁶⁹ Here we focus only on the main findings.

The effective scale height of the atmosphere in the region probed by the occultation was found to be in the range 20–30 km, consistent with previous estimates for the mid-latitude regions of Jupiter from past occultation measurements^{72–76} (but somewhat lower than that measured in the equatorial regions).⁷⁷

A subset of the lightcurves was of sufficient quality (*i.e.* of low enough systematic and random error) to be inverted into atmospheric temperature and density as a function of height or an equivalent parameter (*e.g.* pressure), following previously applied algorithms.⁷⁸ In the interval 3–10 microbar, the profiles appear isothermal with a temperature in the range 160–170K for both ingress and egress (Figure 15 displays ingress profiles), consistent with the calculated temperature of $164 \pm 2\text{K}$ (see Figure 4 in Christou *et al.*⁶⁹). They are in agreement with two profiles⁷⁵ obtained at the same planetographic latitude as our measurements (albeit in the northern hemisphere of the planet) and compare favourably with temperatures of 155–165K measured *in situ* by the Atmospheric Structure Investigation instrument suite on board the *Galileo* Entry Probe over the same pressure range in Jupiter's equatorial region.⁷⁹

A number of non-isothermal, statistically significant, features (alluded to in Raynaud *et al.*⁷⁵) was also identified (see Figure 7 in Christou *et al.*⁶⁹ and discussion therein). They display different distributions at ingress and egress, which has been observed

previously (see Figure 10 in Raynaud *et al.*⁷⁵). Current data sampled similar planetographic latitudes between ingress (49–55° S) and egress (50–58° S) while in Raynaud *et al.*⁷⁵ the latitudes sampled were 73° N and 70° N at ingress and egress, respectively. One interpretation of these differences is either longitudinal or temporal variability at this barometric altitude range in Jupiter's atmosphere. Simultaneous photometric monitoring of future occultation events from as many geographically dispersed sites as possible will help resolve this.

In the next decade, there will be additional opportunities to apply this powerful method to investigate Jupiter's upper atmosphere and look for spatial/temporal variability. The events on 2016 April 12 and on 2021 April 2 merit special attention as they both involve bright stars (<8 mag). The 2016 event, visible from areas of Asia, Oceania, East Africa and Southeast Europe,⁸⁰ samples similar planetographic latitudes at Jupiter as the 45 Cap event.⁸¹ It may take on added significance in view of the expected arrival of the *Juno* mission to the Jovian system.⁸² The 2021 event is visible from North and South America and samples near-equatorial Jovian latitudes. In both cases, the star is also occulted by one of the Galilean satellites, Ganymede in 2016 and Io in 2021. These secondary events may be used to constrain the existence of tenuous atmospheres around these satellites.

3. Summary and conclusions

Interactions between amateur and professional astronomers have changed significantly in the digital era, from an occasional exchanging of individual images to a sustained collaboration through coordinated global networks of amateur astronomers. Today, amateur astronomers with sophisticated equipment and software provide a number of valuable resources to the professional community: a large source of labour, or extension of the professional astronomer's group; a vast collection of data that provides both legacy and temporal information and finally, as ambassadors of science, a group that can help to build bridges between the professional community and the general public. From the professional astronomer/scientist's perspective, given the vast amounts of data acquired through various projects, the natural progression to interactive collaborations between these two communities is tremendously beneficial for science and outreach. The synergy between the two communities has changed the paradigm for scientific research, with the amateur community identifying changes in the atmospheres of giant planets and discovering new phenomena, which allows the professional community to maximise the available resources for scientific results.

Specifically, in the case of Jupiter and Saturn, the integration of amateur and professional data has now identified timescales for various types of intrinsic changes, for example allowing a very detailed characterisation of Jupiter's 2010 SEB revival and Saturn's 2010–11 GWS storm. Extrinsic changes caused by various types of impacts have allowed the creation of a sub-discipline for observations and models. Moreover, Pro-Am studies of rare occultation events allow an investigation of the temperature, pressure, and density profiles in the upper atmospheres of giant planets.

Therefore, the continuous drive by the amateur community to push the limits and the corresponding value of their observations, as presented in this paper, has resulted in a continuous growing number of collaborations with the professional community. We

strongly believe that the synergy between the two communities offers an invaluable resource in the advance of our understanding of Jupiter and Saturn.

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