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Special Section:

Early Results: Juno at Jupiter

Key Points:

- We present the overall cloud morphology of Jupiter over 2016 from images in the spectral range 0.38–1.7 micrometers
- We characterize the equatorial hot spots and present snapshots of the polar regions providing context for observations from Juno
- We measured zonal winds from December 2015 to June 2016 spanning the latitude range 74.5°S–73.2°N without variability over this period

Supporting Information:

- Supporting Information S1

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Jupiter cloud morphology and zonal winds from ground-based observations before and during Juno's first perijove

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Abstract We analyze Jupiter observations between December 2015 and August 2016 in the 0.38–1.7 μm wavelength range from the PlanetCam instrument at the 2.2 m telescope at Calar Alto Observatory and in the optical range by amateur observers contributing to the Planetary Virtual Observatory Laboratory. Over this time Jupiter was in a quiescent state without notable disturbances. Analysis of ground-based images and Hubble Space Telescope observations in February 2016 allowed the retrieval of mean zonal winds from -74.5° to $+73.2^\circ$. These winds did not change over 2016 or when compared with winds from previous years with the sole exception of intense zonal winds at the North Temperate Belt. We also present results concerning the major wave systems in the North Equatorial Belt and in the upper polar hazes visible in methane absorption bands, a description of the planet's overall cloud morphology and observations of Jupiter hours before Juno's orbit insertion.

Plain Language Summary We present a characterization of Jupiter clouds and their dynamics prior to Juno's arrival. We present results based on observations with our own high-resolution instrument PlanetCam, Hubble Space Telescope images acquired in February 2016, and analysis of high-quality images provided by amateur astronomers using small telescopes. Before Juno's arrival to Jupiter its atmosphere behaved in a normal way without major convective outbreaks or changes in its usual belts and bands. Juno's first perijove characterized Jupiter at a time of usual behavior of the planet. Zonal winds were similar to previous years except for high values of the wind velocity at the most intense jet stream in the planet in the North Temperate latitudes which reached values of 157 m/s. We also study two systems of planetary-scale waves in the planet: The first system is north to the equator in the North Equatorial Belt and is characterized by a regular pattern of large dark features in the planet. These are regions of reduced cloud content formed by an atmospheric wave. The second system is an undulatory pattern in the polar hazes that is best observed in the southern hemisphere. Both are characterized for later comparisons with results from the Juno mission.

1. Introduction

Jupiter's meteorology is very rich in the variety of atmospheric phenomena that can be observed at the visible cloud level. Global winds are zonal and alternate in latitude between eastward and westward forming a system of nearly constant jet streams that interact with vortices, turbulent regions, convective storms, and atmospheric waves [Ingersoll et al., 2004; Vasavada and Showman, 2005]. Vortices evolve in size and color and merge or interact with nearby structures [Ingersoll et al., 2004]. Transient events, like convective disturbances, often develop quickly [Sánchez-Lavega and Gómez, 1996; Sánchez-Lavega et al., 2008], and large-scale changes occurring over a few months drastically change the optical properties of bands and belts [Fletcher et al., 2011; Pérez-Hoyos et al., 2012]. Data acquired in the time domain are needed to understand the evolution of meteorological features in the planet. Atmospheric dynamics at the troposphere also have implications for the interpretation of observations of the deep atmosphere [de Pater et al., 2016; Li et al., 2016]. Here we describe the general state of Jupiter's atmosphere over 2016 (cloud morphology, large wave systems, polar regions, and global winds) to present the context of Juno's perijove 1 (PJ1) observations obtained by the MicroWave Radiometer (MWR), Jovian InfraRed Auroral Mapper (JIRAM), and JunoCam instruments in August 2016.

2. Observations

2.1. PlanetCam UPV/EHU and Small Telescope

PlanetCam UPV/EHU [Sánchez-Lavega *et al.*, 2012] is a dual camera that uses the lucky imaging technique [Law *et al.*, 2006] at the 2.2 m telescope in Calar Alto Observatory in Southern Spain. The light from the telescope is separated by a dichroic mirror and sent into two detectors in the wavelength ranges 0.4–1.0 μm (visible) and 1.0–1.7 μm (short wave infrared, SWIR). Mendikoa *et al.* [2016] describe the instrument its optical configurations and filters. Fast images (10–50 images per second) improve the spatial resolution over the seeing by a factor of 3–4, and long exposures are used in narrowband filters sampling methane absorption bands. Images in the visible attain sometimes spatial resolutions on the order of 0.05–0.1 in. (200–350 km over Jupiter at opposition), while images in the SWIR channel typically attain spatial resolutions of 0.09–0.2 in. (300–700 km). In order to get to the maximum spatial resolution, image sharpening techniques are used. Nonsharpened images can be calibrated with observations of spectrophotometric standard stars and enable the study of the vertical distribution of clouds and hazes and the spatial distribution of colors. We ran four Jupiter-observing campaigns from December 2015 to July 2016. We also acquired Jupiter images in several dates using a small 28 cm telescope generally used for astronomy teaching [Sánchez-Lavega *et al.*, 2014]. Figure 1 shows examples of the observations. Supporting information Table S1 provides details of the observations, and supporting information Figures S1–S6 show observations on different dates including 4 July, about 7 h before Juno's orbit insertion.

2.2. Amateur Observations

Amateur astronomers regularly monitor the planet at visible wavelengths at high spatial resolution [Mousis *et al.*, 2014]. Most of the amateur observations used for this study can be retrieved from the Planetary Virtual Observatory and Laboratory (PVOL) database (<http://pvol2.ehu.eus>) [Hueso *et al.*, 2010, 2017]. The database contains more than 1800 observations of Jupiter from December 2015 to Juno's arrival. It also contains global maps of the planet from amateur observations that represent the planet every 10 days approximately and that can also be retrieved from the Unione Astrofili Italiani (<http://pianeti.uai.it/>). Additionally, we selected several pairs of the best amateur observations separated by one to five planetary rotations showing the same side of the planet to measure zonal winds from December to June 2016 following techniques described by Barrado-Izagirre *et al.* [2013]. Supporting information Table S2 details the observations used, and supporting information Figure S7 shows an example of such an image pair.

2.3. HST/OPAL

Hubble Space Telescope (HST) observed Jupiter on 9 and 10 February 2016 as part of its Outer Planets Atmospheric Legacy program (OPAL) [Simon *et al.*, 2015]. We retrieved the images from the Mikulski HST archive and analyzed images in a variety of filters to complement the results here presented.

3. Cloud Morphology

Most of Jupiter's cloud systems from December 2015 to August 2016 are very similar to those observed over 2014–2015 and described from HST observations [Simon *et al.*, 2015]. No major disturbances were observed except for a moderate expansion of the North Equatorial Belt (NEB) from 17°N to 21°N that started in 2015 [Fletcher *et al.*, 2016; Orton *et al.*, 2016].

3.1. Main Ovals

The Great Red Spot (GRS) maintained an intense orange coloration observed since 2014. Several photometric color compositions of the planet from PlanetCam observations show indistinguishable colors in the GRS throughout 2016 (supporting information Figure S8). PlanetCam, amateur, and HST observations show the GRS with a visual longitudinal size of $14.5 \pm 0.2^\circ$ and a latitudinal size of $10.2 \pm 0.2^\circ$. This is slightly larger than reported values over 2015 from HST images with a longitudinal size of 13.9° and a latitudinal size of 9.7° [Simon *et al.*, 2015]. The difference could be due to different measuring methods (we define the size of the GRS as the apparent size of the dark oval in blue wavelength images; our measurements for the GRS size over HST images in 2015 are $13.9 \pm 0.2^\circ$ and $10.2 \pm 0.2^\circ$; see supporting information Figure S9). Amateur and PlanetCam images over December 2015 to July 2016 show a constant size within an uncertainty of 0.2° .

Figure 1. PlanetCam observations close to Jupiter opposition: (a) 890 nm, (b) Johnson I (wideband filter at 806 nm), (c) 1.0–1.7 μm filter (RG1000), and (d) 1190 nm. Images at 890 and 1190 nm are strongly sensitive to methane absorption and provide views of the upper hazes. Images in Johnson I and the 1.0–1.7 μm filter (RG1000) are weakly sensitive to methane absorption and show details up to the polar regions. A North Tropical Oval (nicknamed White Oval Z) later discussed in the text is highlighted in Figure 1b and is barely visible in Figure 1d.

implying that the diminishing size of the GRS over the last decades [Simon *et al.*, 2014] may have reached a stable configuration. Oval BA [Sánchez-Lavega *et al.*, 2001] did not experience major changes over 2016.

The third largest oval in Jupiter is an anticyclone in the boundary between the North Tropical Zone and the northern edge of the North Equatorial Band (NEBn) at 19°N, sometimes nicknamed as White Oval Z. This oval formed in several steps after the consecutive fusion of small ovals, one of them observed since 1997. The current North Tropical Oval (NTrO), with its characteristic morphology, formed in February 2013 after the fusion of two large white ovals, changed from white to red in September 2013 and faded again from red to white later on [Barrado-Izagirre *et al.*, 2015]. Over 2016 this NTrO (Figure 1 and supporting information) had a mean longitudinal size of $7.5 \pm 1.0^\circ$, spanned $4.0 \pm 0.4^\circ$ in latitude, and was surrounded by a faint ring of red material. Observations with PlanetCam in SWIR filters sensitive to weak methane absorption bands (supporting information Figures S1–S3) show this ring with high contrast implying that the coloring agent might be located slightly higher. The complex dynamics of this oval will be presented elsewhere.

3.2. Equatorial Dark Projections

Jupiter's North Equatorial Belt (NEB) hosts a series of compact, quasiperiodic areas of lower cloud content that appear dark in the visible and bright in infrared at 5 μm [Ortiz *et al.*, 1998; Vasavada and Showman, 2005; Arregi *et al.*, 2006]. These dark projections in the visible, or hot spots in 5 μm , have been observed during more than a century at the NEB [Peek, 1958; Rogers, 1995]. In most years they are separated by white plumes, sometimes containing convective sources [Hunt *et al.*, 1982; Stoker, 1986; Hueso and Sánchez-Lavega, 1998]. Plumes and dark projections have been interpreted as the signature of an equatorial planetary wave [Allison, 1990; Showman and Dowling, 2000]. The number of dark projections

(typically 8–12) and their drift speed (from 100 to 115 m s⁻¹) follow a relationship consistent with the superposition of equatorial Rossby waves [Arregi *et al.*, 2006].

Figure 2a shows examples of the evolution of 13 prominent dark projections visible at planetographic latitudes 7–9°. Their drift rates are shown in Figure 2b displaying events of mergings and formation of new dark features. Images in 2016 show a complex evolution of the equatorial dark projections with a variety of sizes and shapes. Some large dark projections diffuse and decrease their size over months (G in Figure 2). Others grow their size, shrink, and grow again (H in Figure 2). The overall drift rate and number of dark projections over 2016 follow the general trend over previous years with a slightly lower mean velocity (102.5 ± 3 m s⁻¹ in System III) that in most years [Arregi *et al.*, 2006].

Feature *j* in Figure 2 is one of the hot spots studied by the JIRAM instrument on Juno's first perijove and is located on 223° in System III (equivalent to 156° in System I) in PJ1 (27 August) [Grassi *et al.*, 2016]. This dark projection formed on 11 July and drifted with a zonal speed of 108 ± 3 m s⁻¹ consistent with motions of nearby hot spots. Figure 2c shows the best image in the visible of this feature which was about 50 days old at the time of the JIRAM observations. A particular initially small, very dark projection formed on 19 July and had an anomalous velocity relative to System III of 81 ± 2 m s⁻¹ at planetographic latitude 8.7°N (T in Figure 2) experiencing major changes in shape and mergings. Figure 2d shows details of its evolution.

3.3. Polar Hazes

Figure 3 shows polar projections from PlanetCam observations in March and May 2016 in methane absorption bands that are sensitive to the high-altitude hazes that cover both poles. These maps of the polar hazes are the firsts obtained from ground-based observations. An additional polar projection of the hazes in 890 nm HST images in February 2016 is available in Figure S10. The southern hemisphere is covered by a homogeneous haze layer that extends from the pole to mean planetographic latitudes $-67^\circ \pm 0.5^\circ$ and is limited by an undulating pattern with varying amplitude in latitude from 1.5 to $2.5^\circ \pm 0.4^\circ$. The wave number of this pattern is $N = 12 \pm 1$ in March 2016 (the ± 1 uncertainty arises from a coverage of only 320° in longitude) and $N = 13$ in May 2016 without uncertainties from global maps. The north polar projections show similar hazes limited at different latitudes by undulating patterns. The most conspicuous system is located at a mean planetographic latitude of $+59^\circ$, and the undulating pattern has amplitudes of 4.0° with wave number $N = 4$ –5. Other wave systems are visible in sectors of the north polar projection at a mean latitude of $+51^\circ$ with a smaller amplitude and larger wave numbers. However, their wave number and phase speed cannot be quantified due to the lower contrast of the images, the superposition of different waves at different latitudes, and limited latitudinal coverage. Both wave systems are those reported by Sánchez-Lavega *et al.* [1998] from Voyager 1 images in 1979 and HST images in 1993 and 1994 and with average phase speed $\langle c \rangle \sim 2$ m s⁻¹ implying that the different wave systems can be explained as planetary Rossby waves. Later analyses of HST [Vincent *et al.*, 2000] and Cassini imaging science system images from December 2000 [Li *et al.*, 2006] and combined analyses of both data sets [Barrado-Izaguirre *et al.*, 2008] also showed very similar characteristics and small phase speeds for the different wave systems. Our current determination of the global wave number for the south polar wave system extends these properties from 1979 to 2016 showing that is a very stable structure surviving at least four Jovian years.

3.4. Polar Clouds

PlanetCam images in narrow infrared (750 ± 5 nm and 935 ± 5 nm) and in wide filters in the SWIR channel (1.0 – 1.7 μ m) probe the upper cloud and provide spatially resolved images of the upper latitudes. Figure 4 shows polar projections of the planet in March 2016 and July 2016. Radiative transfer analysis of past HST and Cassini polar images in visible filters without methane absorption suggests that these features are observed at the 600 ± 200 mbar level [Barrado-Izaguirre *et al.*, 2008]. Compact features, probably small vortices, can be seen up to latitudes $+73^\circ$ and -76° . South polar vortices at -70° seem distributed similarly to the crests and troughs of the south polar wave observed in the upper hazes. The number and distribution of vortices from 60° to 73° suggests that vortices locate homogeneously in area in the polar regions. We cannot extend this conclusion beyond 73° due to the worse image quality at higher latitudes. The temporal sampling of polar regions from ground-based observations contains large gaps and does not allow to study the motions or life cycles of these features. Supporting information Figure S11 shows additional polar projections with different contributions of the upper hazes and lower clouds.

Figure 2. Equatorial dark projections over March–August 2016. (a) Cylindrical maps from amateur images in the latitude range from $\pm 30^\circ$ with dark projections identified in yellow and the NTrO marked in green. (b) Tracks of the major dark projections and their identification. Small dark projections and their interactions appear with grey lines. PlanetCam observations (purple) show the major features and other smaller features not generally visible with small telescopes. Empty circles correspond to measurements on individual images. The red line and red dots (T) shows the anomalously slow dark feature. A red star shows the position of a particular hot spot that was observed by JIRAM on Juno [Grassi et al., 2016]. Green dashed line shows the date for Juno's orbit insertion and green dotted line Juno's PJ1. (c) Daylight observation on 15 August in infrared wavelengths with a cutoff filter at 742 nm. We highlight feature *j* observed by JIRAM on Juno 10 days later. Orange line in Figure 2b shows longitudes covered in this image. Image by T. Barry. (d) Morphological evolution of the slow feature T.

Figure 3. Stereographic polar projections of both poles in strong methane absorption bands. The (a) 3 and 4 March 2016 in 890 nm and (b) 17 to 19 May 2016 in 1190 nm. Longitudes are displayed so that rotation is clockwise in the northern hemisphere and anticlockwise in the southern hemisphere.

4. Zonal Winds

4.1. Ground-Based Observations

The first global zonal wind profile of Jupiter based on amateur and Pic du Midi images alone was published by Barrado-Izagirre *et al.* [2013] for data acquired in 2011. We follow a similar procedure and selected 26 image pairs separated in time from one to a few Jupiter rotations using amateur observations from small telescopes available in the PVOL database [Hueso *et al.*, 2010, 2017] and Association of Lunar and Planetary Observers (ALPO) Japan (<http://alpo-j.asahikawa-med.ac.jp/indexE.htm>), images from our PlanetCam UPV/EHU data set, and from the Pic du Midi 1 m telescope. Images were cylindrically projected, limb-darkened corrected, and compared using image correlation algorithms [Hueso *et al.*, 2009; Barrado-Izagirre *et al.*, 2013]. Supporting information Table S2 details the observations and includes the names of the observers. We obtained 23,820 measurements from planetographic latitudes $-68, 5^{\circ}$ to $70, 3^{\circ}$. The mean value of the standard deviation of measurements for latitude bins of 0.1° is $\sim 7.5 \text{ m s}^{-1}$.

4.2. HST/OPAL

We analyzed all the HST images from 9 and 10 February 2016 in the red F631 N filter following the same technique. We obtained 19,100 wind measurements from planetographic latitudes -74.5° to $+73.2^{\circ}$. The global dispersion of the measurements is 3.7 m s^{-1} from the mean value of the standard deviation of measurements in latitudinal bins of 0.1° . This value is below the diffraction limit of the HST/WFC3 which would result in uncertainties on the order of 5.8 m s^{-1} for images at 631 nm separated in time by 10 h. The lower value comes from the fact that at least six image pairs were used to measure winds at each latitude.

Figure 4. Stereographic polar projections of both poles at broad filters in long wavelengths. (a) The 3 and 4 March 2016 integrating light from 1.0 to 1.7 μm . These panels can be compared with Figure 3a. (b) The 4 July in band J (1.25 μm) partially sensitive to methane absorption but able to uncover part of the lower clouds. Colored arrows indicate compact features (probably vortices) at latitudes higher than 60°. A chain of vortices at 58° is highlighted in Figure 4a.

HST and ground-based mean zonal winds are compared in Figure 5. Zonal winds from HST images are more precise and extend to higher latitudes. Wind results from ground-based observations capture the overall shape of the zonal winds and are in very good agreement with HST, although they miss a bit the highest winds at the peaks of the zonal jets due to the limited spatial resolution. Differences between both zonal wind profiles are below 3.7 m s^{-1} , equivalent to the measured noise level of HST images. The motivations to obtain the ground-based zonal winds were the following:

1. Explore the possibility of small temporal changes in the zonal winds at different latitudes over 2016. A full statistical analysis of the ground-based data from December 2015 to June 2016 and a comparison with HST zonal winds measured in January 2015 [Simon *et al.*, 2015] including a specific exploration of the NTB jet (not shown) conclude that there were no changes in the zonal winds at any latitude below the amateur noise level (10 m s^{-1} for the worse statistics associated to data from individual months).
2. Validate the technique for ground-based data which provides results that largely improve in terms of better latitudinal resolution and smaller error bars over previous analyses with similar data [Barrado-Izagirre *et al.*, 2013].

Differences between the 2016 zonal winds and Cassini winds concentrate in (i) the North Temperate Belt (NTB) with intense zonal winds in 2015 [Simon *et al.*, 2015] and 2016 possibly required for the development of large-scale disturbances [Sánchez-Lavega *et al.*, 2008, 2017], (ii) the NEB where the presence of large dark projections moving more slowly than the winds makes zonal winds apparently less intense

Figure 5. Jupiter zonal winds in 2016. (a) Zonal winds from HST images in the F631 filter (blue) compared with zonal winds from ground-based observations (magenta) together with a reference zonal wind profile from Cassini in 2000 (black with grey error bar) [Porco *et al.*, 2003]. (b) Standard deviations of the 2016 HST (blue) and ground-based (magenta) data. (c) Number of measurements per latitudinal bin of 0.1° for both data sets (HST in blue; ground based in magenta). (d) Differences between both 2016 profiles (black) are generally below the measurement noise level from HST of $\pm 3.7 \text{ m s}^{-1}$ (green). Standard deviations of the zonal wind differences are shown with red lines showing that differences are below the combined measurement noise.

[Asay-Davis *et al.*, 2011; Barrado-Izagirre *et al.*, 2013; Choi *et al.*, 2013], and (iii) the peak of the SEB jet where a wave system partially observed over 2015 may also affect the zonal winds resulting in less intense motions [Rogers *et al.*, 2016].

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5. Conclusions

From December 2015 to August 2016 Jupiter displayed a quiescent meteorological activity without large disturbances or alterations of its global pattern of belts and zones. The GRS decreasing size seems to have stopped over 2015 and 2016. Equatorial hot spots were large, well contrasted, and numerous ($N = 13 \pm 1$) over most of the year and followed the classical behavior of an equatorial Rossby wave [Allison, 1990; Arregi *et al.*, 2006]. The polar regions were covered by high hazes that show a Rossby wave behavior ($N = 12 \pm 1$ in the southern hemisphere), and their observed characteristics matched historical observations since 1979. Zonal winds could be measured over different temporal periods without noticeable changes except for a high value of the NTB jet which peaked at $157 \pm 3 \text{ m s}^{-1}$. These high speeds of the NTB jet seem to occur previous to the development of large-scale convective outbreaks [Sánchez-Lavega *et al.*, 2008] as the one developed in October 2016 [Sánchez-Lavega *et al.*, 2017]. PlanetCam observations of the polar regions at filters not sensitive to methane absorption provide dynamical context to the high-resolution polar observations of JunoCam [Orton *et al.*, 2017]. Our study of the evolution of the NEB dark projections over 2016 provides temporal context to JIRAM observations of the equatorial hot spots.

References

- Allison, M. (1990). Planetary waves in Jupiter's equatorial atmosphere, *Icarus*, 83, 282–307, doi:10.1016/0019-1035(90)90069-L.
- Arregi, J., J. F. Rojas, A. Sánchez-Lavega, and A. Morgado (2006). Phase dispersion relation of the 5-micron hot spot wave from a long-term study of Jupiter in the visible, *J. Geophys. Res.*, 111, E09010, doi:10.1029/2005JE002653.
- Asay-Davis, X. S., P. S. Marcus, M. H. Wong, and I. de Pater (2011). Changes in Jupiter's zonal velocity between 1979 and 2008, *Icarus*, 211(2), 1215–1232, doi:10.1016/j.icarus.2010.11.018.
- Barrado-Izagirre, N., J. F. Rojas, R. Hueso, A. Sánchez-Lavega, F. Colas, J. L. Dauvergne, D. Peach and the IOPW Team (2013). Jupiter's zonal winds and their variability studied with small-size telescopes, *Astron. Astrophys.*, 554(A74), 11, doi:10.1051/0004-6361/201321201.

- Barrado-Izagirre, N., J. Legarreta, A. Sánchez-Lavega, R. Hueso, S. Pérez-Hoyos, J. F. Rojas and I. Mendikoa (2015), A long-lived and color changing oval on Jupiter's NTrZ (at 19°N), Abstract P41B-2068 presented at 2010 Fall Meeting, AGU, San Francisco, Calif.
- Barrado-Izagirre, N., A. Sánchez-Lavega, S. Pérez-Hoyos, and R. Hueso (2008), Jupiter's polar clouds and waves from Cassini and HST images: 1993–2006, *Icarus*, 194(1), 173–185, doi:10.1016/j.icarus.2007.08.025.
- Choi, D. S., A. P. Showman, A. R. Vasavada, and A. A. Simon-Miller (2013), Meteorology of Jupiter's equatorial hot spots and plumes from Cassini, *Icarus*, 223(2), 832–843, doi:10.1016/j.icarus.2013.02.001.
- de Pater, I., R. J. Sault, B. Butler, D. DeBoer, and M. H. Wong (2016), Peering through Jupiter's clouds with radio spectral imaging, *Science*, 352(6290), 1198–1201, doi:10.1126/science.aaf2210.
- Fletcher, L. N., G. S. Orton, J. H. Rogers, A. A. Simon-Miller, I. de Pater, M. H. Wong, O. Mousis, P. G. J. Irwin, M. Jacquesson, and P. A. Yanamandra-Fisher (2011), Jovian temperature and cloud variability during the 2009–2010 fade of the South Equatorial Belt, *Icarus*, 213(2), 564–580, doi:10.1016/j.icarus.2011.03.007.
- Fletcher, L. N., G. S. Orton, T. K. Greathouse, J. Sinclair, R. Giles, P. Irwin, J. Rogers and T. Encenaz (2016), Jupiter's thermal structure on the eve of Juno's arrival and an NEB expansion event, EGU2016-13076.
- Grassi, D., et al. (2016), Juno-JIRAM: Overview of preliminary results in the study of Jupiter hot-spots, Abstract P24B-03 presented at 2010 Fall Meeting, AGU, San Francisco, Calif.
- Hueso, R., and A. Sánchez-Lavega (1998), Motions in Jovian hot spot-plume regions using Voyager images, *Icarus*, 136, 353–357, doi:10.1006/icar.1998.6018.
- Hueso, R., J. Legarreta, E. García-Melendo, A. Sánchez-Lavega, and S. Pérez-Hoyos (2009), The jovian anticyclone BA: II. Circulation and interaction with the zonal jets, *Icarus*, 203(2), 499–515, doi:10.1016/j.icarus.2009.05.004.
- Hueso, R., J. Legarreta, S. Pérez-Hoyos, J. F. Rojas, A. Sánchez-Lavega, and A. Morgado (2010), The international outer planets watch atmospheres node database of giant planets images, *Planet. Space Sci.*, 58(10), 1152–1159, doi:10.1016/j.pss.2010.04.006.
- Hueso, R., J. Juaristi, J. Legarreta, A. Sánchez-Lavega, J. F. Rojas, S. Erard, B. Cecconi, P. Le Sidaner (2017), The Planetary Virtual Observatory and Laboratory (PVOL) and its integration into the Virtual European Solar and Planetary Access (VESSPA), *Planet. Space Sci.*, doi:10.1016/j.pss.2017.03.014.
- Hunt, G. E., J. P. Müller, and P. Gee (1982), Convective growth rates of equatorial features in the jovian atmosphere, *Nature*, 295, 491–494, doi:10.1038/295491a0.
- Ingersoll, A. P., T. E. Dowling, P. J. Gierasch, G. S. Orton, P. L. Read, A. Sánchez-Lavega, A. P. Showman, A. A. Simon-Miller, and A. R. Vasavada (2004), *Jupiter: The Planet, Satellites and Magnetosphere*, edited by F. Bagenal, T. E. Dowling, and W. B. McKinnon, pp. 105–128, Cambridge Univ. Press, Cambridge, U. K.
- Law, N. M., C. D. Mackay, and J. E. Baldwin (2006), Lucky imaging: High angular resolution imaging in the visible from the ground, *Astron. Astrophys.*, 446(2), 739–745, doi:10.1051/0004-6361:20053695.
- Li, L., A. P. Ingersoll, A. R. Vasavada, A. A. Simon-Miller, A. D. Del Genio, S. P. Ewald, C. C. Porco, and R. A. West (2006), Vertical wind shear on Jupiter from Cassini images, *J. Geophys. Res.*, 111, E04004, doi:10.1029/2005JE002556.
- Li, C., A. P. Ingersoll, M. A. Janssen (2016), Retrievals of atmospheric parameters from radiances obtained by the Juno microwave radiometer, Abstract P33C-2167 presented at 2010 Fall Meeting, AGU, San Francisco, Calif.
- Mendikoa, I., A. Sánchez-Lavega, S. Pérez-Hoyos, R. Hueso, J. F. Rojas, J. Aceituno, F. Aceituno, G. Murga, L. de Bilbao, and E. García-Melendo (2016), PlanetCam UPV/EHU: A two-channel lucky imaging camera for solar system studies in the spectral range 0.38–1.7 μm , *Publ. Astron. Soc. Pac.*, 128(961), 035002, doi:10.1088/1538-3873/127/961/035002.
- Mousis, O., et al. (2014), Instrumental methods for professional and amateur collaborations in planetary astronomy, *Exp. Astron.*, 38(1–2), 91–191, doi:10.1007/s10686-014-9379-0.
- Ortiz, J. L., G. S. Orton, A. J. Friedson, S. T. Stewart, B. M. Fisher, and J. R. Spencer (1998), Evolution and persistence of 5- μm hot spots at the Galileo Probe entry latitude, *J. Geophys. Res.*, 103(E10), 23,051–23,069, doi:10.1029/98JE00696.
- Orton, G. S., et al. (2016), Activity in Jupiter's northern hemisphere before the Juno Mission: Waves associated with the North Equatorial Belt and relation to expansion phase, DPS meeting 48, id.501.09.
- Orton, G. S., et al. (2017), The first close-up images of Jupiter's polar regions: results from the Juno mission JunoCam instrument, *Geophys. Res. Lett.*, 44, doi:10.1002/2016GL072443.
- Peek, B. M. (1958) *The Planet Jupiter*, Faber and Faber, London.
- Pérez-Hoyos, S., J. F. Sanz-Requena, N. Barrado-Izagirre, J. F. Rojas, A. Sánchez-Lavega, and I. O. P. W. Team (2012), The 2009–2010 fade of Jupiter's South Equatorial Belt: Vertical cloud structure models and zonal winds from visible imaging, *Icarus*, 217(1), 256–271, doi:10.1016/j.icarus.2011.11.008.
- Porco, C., et al. (2003), Cassini imaging of Jupiter's atmosphere, satellites and rings, *Science*, 299(5612), 1541–1547, doi:10.1126/science.1079462.
- Rogers, J. H. (1995), *The Giant Planet Jupiter*, Cambridge Univ. Press, Cambridge, U. K.
- Rogers, J. H., L. N. Fletcher, G. Adamoli, M. Jacquesson, M. Vedovato, and G. S. Orton (2016), A dispersive wave pattern on Jupiter's fastest retrograde jet at 20°S, *Icarus*, 277, 354–369, doi:10.1016/j.icarus.2016.05.028.
- Sánchez-Lavega, A., and J. M. Gómez (1996), The South Equatorial Belt of Jupiter. I: Its life cycle, *Icarus*, 121, 1–17, doi:10.1006/icar.1996.0067.
- Sánchez-Lavega, A., R. Hueso, and J. R. Acarreta (1998), A system of circumpolar waves in Jupiter's stratosphere, *Geophys. Res. Lett.*, 25(21), 4043–4046, doi:10.1029/1998GL900059.
- Sánchez-Lavega, A., et al. (2001), The merger of two giant anticyclones in the atmosphere of Jupiter, *Icarus*, 149(2), 491–495, doi:10.1006/icar.2000.6548.
- Sánchez-Lavega, A., et al. (2008), Depth of a strong jovian jet from a planetary-scale disturbance driven by storms, *Nature*, 451(7177), 437–440, doi:10.1038/nature06533.
- Sánchez-Lavega, A., et al. (2012), PlanetCam UPV/EHU: A simultaneous visible and near infrared lucky-imaging camera to study solar system objects, *Proc. SPIE*, 8446, 84467X-1 - 84467X-9, doi:10.1117/12.926149.
- Sánchez-Lavega, A., S. Pérez-Hoyos, R. Hueso, T. del Río-Gaztelurrutia, and A. Oleaga (2014), The Aula Espazio Gela and the Master of Space Science and Technology in the Universidad del País Vasco (University of the Basque Country), *Eur. J. Eng. Educ.*, 39, 518–526, doi:10.1080/03043797.2013.788611.
- Sánchez-Lavega, A., et al. (2017), A planetary-scale disturbance in the most intense Jovian atmospheric jet from JunoCam and ground-based observations, *Geophys. Res. Lett.*, doi:10.1002/2017GL073421, in press.
- Stoker, C. R. (1986), Moist convection—A mechanism for producing the vertical structure of the Jovian equatorial plumes, *Icarus*, 67, 106–125, doi:10.1016/0019-1035(86)90179-X.
- Showman, A. P., and T. E. Dowling (2000), Nonlinear simulations of Jupiter's 5-micron hot spots, *Science*, 289(5485), 1737–1740, doi:10.1126/science.289.5485.1737.

- Simon, A. A., M. H. Wong, J. H. Rogers, G. S. Orton, I. de Pater, X. Asay-Davis, R. W. Carlson, and P. S. Marcus (2014), Dramatic change in Jupiter's Great Red Spot from spacecraft observations, *Astrophys. J. Lett.*, 797(2), L31, 4, doi:10.1088/2041-8205/797/2/L31.
- Simon, A. A., M. H. Wong, and G. S. Orton (2015), First results from the Hubble OPAL program: Jupiter in 2015, *Astrophys. J. Lett.*, 812(1), 55, 8, doi:10.1088/0004-637X/812/1/55.
- Vasavada, A. R., and A. P. Showman (2005), Jovian atmospheric dynamics: An update after Galileo and Cassini, *Rep. Prog. Phys.*, 68(8), 1935–1996, doi:10.1088/0034-4885/68/8/R06.
- Vincent, M. B., et al. (2000), Jupiter's polar regions in the ultraviolet as imaged by HST/WFPC2: Auroral-aligned features and zonal motions, *Icarus*, 143(2), 205–222, doi:10.1006/icar.1999.6233.