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1 **A PLANETARY-SCALE DISTURBANCE IN A LONG LIVING THREE VORTEX**
2 **COUPLED SYSTEM IN SATURN'S ATMOSPHERE**

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24 **Keywords**

25 Saturn; Atmospheres, dynamics; Saturn, atmosphere; Hubble Space Telescope
26 observations

27
28 **Abstract**

29 The zonal wind profile of Saturn has a unique structure at 60°N with a double-peaked jet
30 that reaches maximum zonal velocities close to 100 ms⁻¹. In this region, a singular group
31 of vortices consisting of a cyclone surrounded by two anticyclones was active since 2012
32 until the time of this report. Our observation demonstrates that vortices in Saturn can be
33 long-lived. The three-vortex system drifts at $u=69.0\pm 1.6$ ms⁻¹, similar to the speed of the
34 local wind. Local motions reveal that the relative vorticity of the vortices comprising the
35 system is ~2-3 times the ambient zonal vorticity. In May 2015, a disturbance developed
36 at the location of the triple vortex system, and expanded eastwards covering in two
37 months a third of the latitudinal circle, but leaving the vortices essentially unchanged. At
38 the time of the onset of the disturbance, a fourth vortex was present at 55°N, south of the
39 three vortices and the evolution of the disturbance proved to be linked to the motion of
40 this vortex. Measurements of local motions of the disturbed region show that cloud
41 features moved essentially at the local wind speeds, suggesting that the disturbance
42 consisted of passively advecting clouds generated by the interaction of the triple vortex
43 system with the fourth vortex to the south. Nonlinear simulations are able to reproduce
44 the stability and longevity of the triple vortex system under low vertical wind shear and
45 high static stability in the upper troposphere of Saturn.

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47 **1. Introduction**

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49 Vortices in Saturn are difficult to see from ground-based telescopic imaging because of
50 their relatively small size and low albedo contrast. Prior to Cassini spacecraft's arrival to
51 the planet in 2004, most Saturnian vortices were detected either during the Voyager flybys
52 in 1980-81 (Smith et al., 1980, 1981; Ingersoll et al., 1984; Sánchez-Lavega et al., 1993,

53 Sanchez-Lavega et al., 1997; García-Melendo and Sánchez-Lavega, 2007), or in
54 observations taken by the Hubble Space Telescope (HST) (Sánchez-Lavega et al., 2003,
55 2004). Since 2004, Cassini has provided a more continuous coverage of the atmospheric
56 features of the planet. Several studies have analyzed the size, morphology, lifetime and
57 latitudinal distribution of different vortices observed by the Imaging Science Subsystem
58 (ISS) (Vasavada et al., 2006, Del Genio et al., 2009, del Río-Gaztelurrutia et al., 2010,
59 Sayanagi et al. 2013, 2014, Trammell et al., 2014) and by the Visual and Infrared
60 Mapping Spectrometer (VIMS) instrument (Baines et al., 2009; Dyudina et al., 2007).
61 These analyses provide important clues on the large-scale dynamics of Saturn's
62 atmosphere (Trammell et al., 2014, Trammell et al., 2016). In particular, numerical
63 modeling of these systems shows the atmospheric conditions at deep levels of the weather
64 layer under which the Saturn vortices are stable (García-Melendo et al., 2007, del Río-
65 Gaztelurrutia et al., 2010). Thus, the existence and evolution of long-lived vortices are
66 key to understanding the atmospheric conditions beneath the observable upper clouds.

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68 The zonal wind profile of Saturn, like that of Jupiter, is approximately symmetric in
69 latitude, with a strong prograde (eastward) equatorial jet and four other eastward jets in
70 the North and South hemispheres. The jet around $+60^\circ$ planetocentric latitude has a
71 distinct double-peak structure and reaches maximum zonal velocities close to 100 ms^{-1}
72 (Figure 1). This feature of the jet is stable in time: It was present in 1981, when the
73 Voyagers' flybys allowed measurements of zonal wind with sufficient latitudinal
74 resolution (Sánchez-Lavega et al., 2000) and it was also observed by Cassini (Vasavada
75 et al., 2006; García-Melendo et al., 2011). However, this double-peak structure is not
76 present in any other wind jet either in Saturn or in Jupiter (García-Melendo et al., 2001;
77 Porco et al., 2003).

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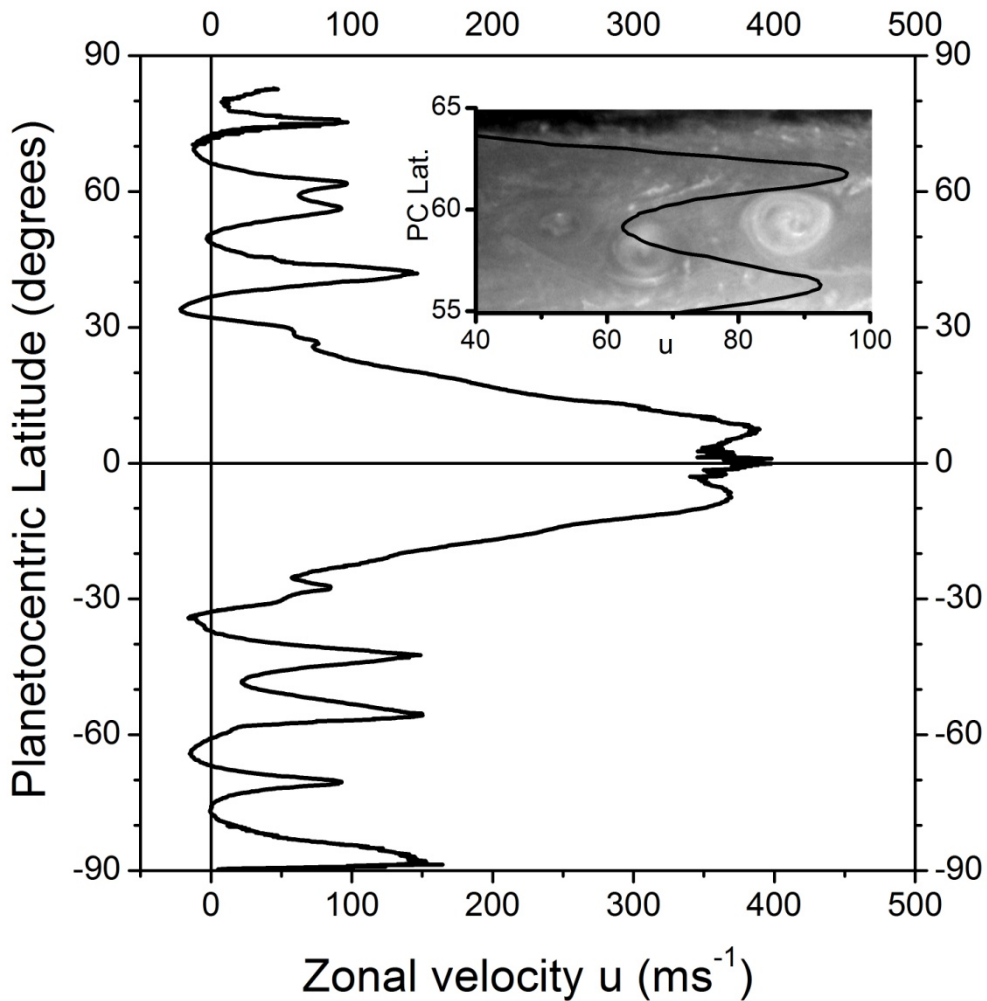


Figure 1. Zonal wind velocity profile of Saturn. Inset shows the double peak jet between 55° and 65°N , together with a cylindrical projection of the triple vortex system.

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In Jupiter, cyclonic and anticyclonic vortices tend to form between jet peaks, in regions with low wind velocity and weak meridional vorticity gradient. These Jovian vortices drift at velocities not identical to the local winds (Simon and Beebe 1996, Li et al., 2004, Del Genio et al., 2009, Ingersoll et al. 2004). In Saturn, vortices have been observed drifting zonally at high velocities, and in regions with weak vorticity gradient, suggesting that cyclones and anticyclones tend to form close to the inflection point of the jet curvature ($d^2u/dy^2 = 0$) In the case of Saturn, the precise rotation rate of the planet has not been yet determined (Del Genio et al., 2009) but, as is standard, we adopt System III West longitudes (Archinal et al., 2011) to compute zonal winds. Although a change in the rotation period within the values proposed so far would change the values of zonal velocities, it would not change the meridionally alternating shape of the zonal wind profile (Sánchez-Lavega, 2005) and the values of vorticity. The twin peaks of the 60°N jet mark two distinct dynamical regions, very close in latitude, with similar rather high eastward velocity but with opposite ambient vorticity. Thus, the jet structure in this region of Saturn facilitates the coupling of ovals of opposite vorticity North and South of the local minimum of velocity in the region of the double peak jet.

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Trammel et al. (2016) analyzed Saturn’s northern hemisphere from 2009 to 2015 and found that, with the exception of the large anticyclone that developed after the Great White Storm of 2010 (Sánchez-Lavega et al., 2012; Sayanagi et al., 2013), vortices had a lifetime of less than a year, and that the number of vortices varied in a significant way in the period of study. In their work, they did not concentrate in a particular region of the hemisphere, and their estimate of the lifetime of the vortices was based on temporal changes in vortex statistics rather than tracking individual vortices.

This work focuses on the region between 55 °N and 65 °N around the double peaked jet. We briefly describe the temporal evolution of the vortices in that region between 2007 and 2016 and then we focus our analysis on a long-lived system of one cyclone and two anticyclones that started interacting around 2012. This coupled system is still visible in images of Saturn at the end of 2016 and thus has survived for at least four years. In what follows, we shall refer to the triple vortex system as Anticyclone-Cyclone-Anticyclone abbreviated as ACA system (Figure 1, inset). In May 2015, a large disturbance developed at the location of ACA system, prominent enough to be observable in ground-based images captured with small telescopes. This disturbance expanded quickly in longitude following the zonal winds and covered approximately a third of the longitudinal circle. The disturbance faded by July 2015 but the ACA system survived and remained essentially unchanged, illustrating the remarkable stability of the system.

Other well-known cases of anticyclone-cyclone-anticyclone systems occurred on Jupiter during the mergers of White Ovals at 33°S latitude that eventually became the present-day Oval BA (Sánchez-Lavega et al 2001, Hueso et al 2009). These ovals, nicknamed BC, DE and FA, formed around 1940 as long elongated white sectors in a Jovian band and then shrunk progressively until they reached about 10,000 km in the east-west direction (see e.g. Rogers, 1995). During their lifetime, these ovals wandered in longitude, approaching and separating as if they repelled each other. In 1998, BC and DE approached very closely; initially, a cyclonic cell between them impeded their approach, forming a compact anticyclone-cyclone-anticyclone system. However, subsequent interaction of the northern edge of the three vortex system with the southern edge of Jupiter’s Great Red Spot (GRS) displaced the cyclone meridionally and led to the merger of BC and DE, forming BE (Sánchez-Lavega et al, 1999). One year later, a merger between BE and FA followed a similar sequence of events and formed the anticyclone BA (Sánchez-Lavega et al, 2001), still present in the atmosphere of Jupiter (Simon et al., 2015). The longevity of the vortices and their sudden merger was explained by Youssef and Marcus (2003), while the cause of an intriguing and lasting change in color from white to red has been addressed by, e.g., de Pater et al., 2010; Wong et al., 2011; Marcus et al., 2013.

The objective of the research presented in this paper is to conduct a detailed study of Saturn’s ACA system and the disturbance that developed at the location of the system in May 2015, in an attempt to establish its origin. In section 2, we describe our data and methods of analysis. In section 3, we establish the lifetime and long time evolution of the ACA system and in section 4, we present its morphology and local motions. Section 5 is dedicated to an analysis of the perturbation that developed in May 2015. In section 6, we include some numerical analyses of the stability of vortices in the double peaked jet. In section 7, we summarize our conclusions.

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2. Data and Methods

The images we analyze in this work can be classified in three sets. A first set comprises images taken by the ISS instrument onboard Cassini (Porco et al., 2004) using both the Wide Angle Camera (WAC) and the Narrow Angle Camera (NAC). Those images have a wide range of spatial resolutions and are mostly captured at filters covering methane absorption bands MT2, MT3 and their corresponding continuum filters CB2 and CB3, which allow easier identification of the features under analysis. They cover the period 2007-2016. A second set includes three groups of images taken with a variety of filters in three different orbits by the Wide Field Camera 3 (WFC3) onboard HST, on June 29-30 and July 1, 2015 (Sánchez-Lavega et al., 2016). A final set of images consists of images retrieved from the International Outer Planets Watch (IOPW) network hosted at the Planetary Virtual Observatory and Laboratory (PVOL) database¹ (Hueso et al., 2010a, 2017), which provides access to very good quality planetary images obtained by amateur astronomers. In Table 1, we present a summary of the images used and some of their characteristics.

Table 1: Summary of the images used in this study.

Local motions and morphology description of the ACA system				
<i>Instrument</i>	<i>Filters</i>	<i>Date</i>	<i>Resolution (km/pixel)</i>	<i>N</i>
Cassini ISS (WAC and NAC)	CB2 / MT2	27 Feb 2013	36/72	4
	MT3	9 Feb 2015	120	1
	MT3	25 May 2015	140	1
	MT3	7 Sep 2015	227	1
HST WFC3	FQ937N/ FQ889N F336W	29 Jun -1 Jul 2015	300	5
Morphology of the cyclone				
<i>Instrument</i>	<i>Filter</i>	<i>Date</i>	<i>Resolution (km/pixel)</i>	<i>Phase Angle</i>
Cassini ISS (WAC and NAC)	CB2	13 Jan 2008	68.3	58.5
	CB2	21 Jan 2009	51.6	55.4
	CB2	25 Jul 2010	60.7	29.6
	CB2	27 Nov 2012	39.2	12.5
	CB2	17 Aug 2013	63.1	26.2
	CB2	3 Apr 2014	12.4	38.0
Long term tracking				
<i>Source</i>	<i>Dates</i>		<i>Resolution (km/pixel)</i>	<i>N</i>
Cassini ISS WAC	8 Jul 2007 – 8 Sep 2015		36 - 450	78
HST WFC3	29 Jun 2015- 1 Jul 2015		300	9
IOPW-PVOL	30 Jan 2015- 19 Sep 2015		1000	69

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Images obtained by Cassini ISS are navigated using the software PLIA (Hueso et al., 2010b). This software uses SPICE kernels to assign latitude and longitude to each image pixel, and allows fine adjustment of the navigation when the limb is visible in the image. The HST/WFC3 images are navigated with Simnav, a custom-made software written in

¹ The PVOL database is available at <http://pvol2.ehu.eus>

177 IDL, which assigns latitude, longitude, emission, and incident angle values to each pixel
 178 by aligning a synthetic planetary disk to the science data (Lii et al. 2010). This method
 179 treats images as orthographic projections, and achieves subpixel alignment accuracy.
 180 Finally, images from the PVOL database were navigated via limb-fitting using the
 181 software LAIA (<http://www.ajax.ehu.es/>). Throughout this report, latitudes are
 182 planetocentric and longitudes are in Saturn System III (Archinal et al., 2010).

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184 Low-resolution PVOL images and Cassini ISS WAC images are used in combination for
 185 the long-term analysis of the ACA system. Errors in latitude in the analysis of the long-
 186 term motion are represented by the standard deviation of the values of the whole data set.
 187 The average zonal velocity is deduced from the linear fit to the longitudinal drift using
 188 the expression:

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$$190 \quad u = R(\varphi_{PC}) \cos \varphi_{PC} \frac{d\lambda}{dt} \quad (1)$$

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192 where u is the zonal velocity, φ_{PC} is the planetocentric latitude, $R(\varphi_{PC})$ the radius of
 193 Saturn at latitude φ_{PC} and $d\lambda/dt$ the drift in longitude measured in radians per second.

194 The long temporal intervals involved imply that the error in the determination of the mean
 195 longitudinal drift is very small, and the main error in zonal velocities arises from the error
 196 in the determination of the latitude, since at the high latitudes involved in this study, the
 197 length of the longitudinal circle varies strongly with latitude. We have estimated the error
 198 in velocity using the expression:

199

$$200 \quad \Delta u \approx u \tan \varphi_{PC} \Delta \varphi_{PC}, \quad (2)$$

201

202 leading to errors of the order of 1.5 ms^{-1} for a typical error of 0.7° in latitude and a velocity
 203 of 70 ms^{-1} .

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205 Local wind speeds are measured in the high-resolution Cassini ISS WAC images and
 206 HST WFC3 images assuming that cloud features advect with the local wind as passive
 207 tracers. We have used a combination of two different methods to measure wind speeds:
 208 manual cloud tracking of individual features and a supervised brightness correlation
 209 method (Hueso et al. 2010b). To analyze the cloud motion inside of the ACA system in
 210 high resolution, we analyze pairs of Cassini ISS images separated in time by
 211 approximately two hours. The images are first transformed in cylindrical map projections
 212 (Snyder, 1987), and analyzed using the supervised brightness correlation method to
 213 determine the zonal and meridional displacement of trackable features. In this case, due
 214 to the short time interval between the images, the main source of error in the
 215 determination of velocities is navigation uncertainty. We determine the uncertainties of
 216 those measurements using the pixel scale p and the time interval between images Δt as
 217 $\Delta u \approx p / \Delta t$ for one-pixel uncertainty on the location of the navigation grid, which makes
 218 the total uncertainty approximately 5 ms^{-1} in our analysis of CB2 images of February
 219 2013.

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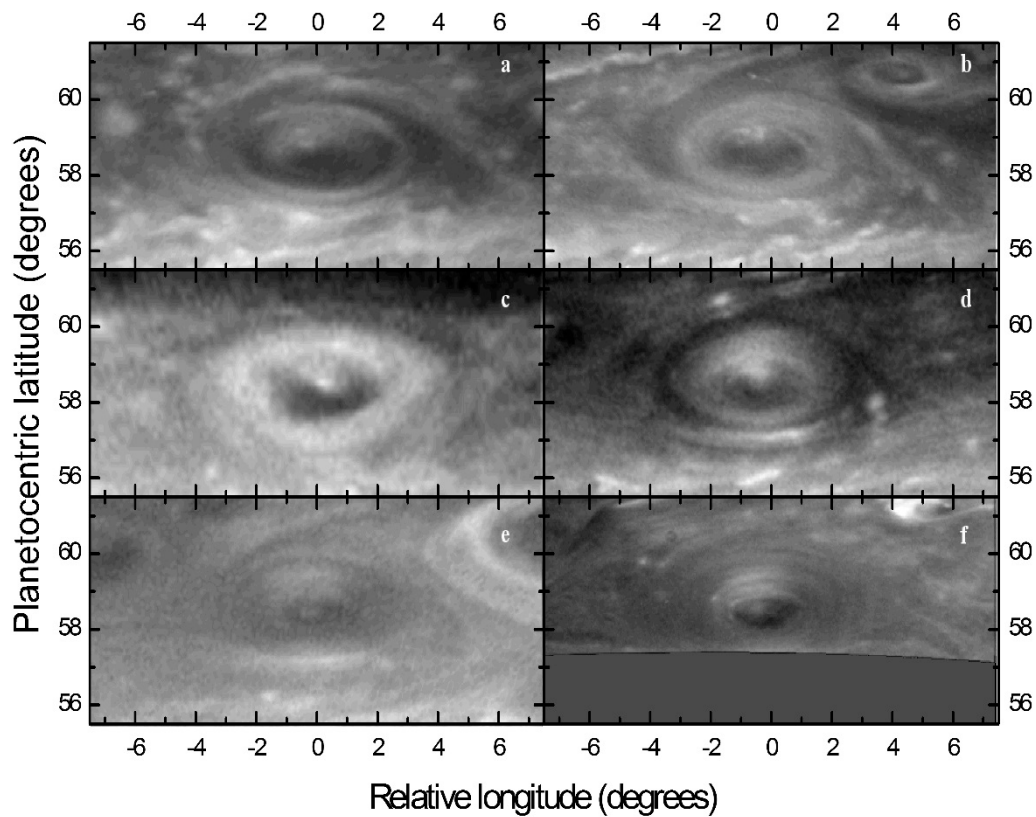
221 In the analysis of the planetary disturbance, we analyze HST/WFC images that cover a
 222 large portion of the planet with images separated by two Saturn rotations. The images are
 223 mapped in polar projections to allow easier identification of the features. In this case,
 224 zonal winds have been measured using visual cloud tracking of the most prominent
 225 features. Whenever possible, linear fits to the cloud motions are performed to determine

226 their long-term mean motion. Error in those measurements is due mainly to the inferior
227 resolution and uncertainties in the feature positions due to the evolution of the identified
228 features, and it has been estimated as $\Delta u \approx d / \Delta t$, where d is the estimated uncertainty in
229 a feature position, leading to a combined uncertainty of approximately 4 ms^{-1} .
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231 **3. History of the ACA vortex system**

232 In order to study the long-term evolution of the ACA system, we surveyed Cassini images
233 of Saturn's Northern sub-polar latitudes surrounding the double-peaked jet, from 50° to
234 65° planetocentric latitude (see Figure 1). The first Cassini views of this region were
235 obtained in mid-2007, showing a number of moderately sized but well-formed vortices.
236 Vortices of similar appearance can be identified up to the end of 2015 whenever the region
237 was visible by Cassini at enough spatial resolution but there are significant large gaps in
238 the temporal coverage of these latitudes.
239

240 At the latitudes corresponding to the cyclonic region of the double peak jet, $\sim 58.5^\circ\text{N}$ (the
241 region south of the westward local minimum in the zonal wind) images captured in July
242 2007 show the presence of an oval-shaped vortex. All later maps of this latitudinal band
243 at high enough spatial resolution reveal the presence of just one similar vortex at that
244 latitude. Figure 2 shows those cyclones at six different epochs, showing that while there
245 are some changes in the cloud morphology, there are no great changes in size or general
246 aspect, reminiscent of the long-lived cyclone tracked during four years (2004-2008) in
247 Saturn's South Hemisphere (del R o-Gaztelurrutia et al., 2010). In the present case, an
248 attempt to check if all images correspond to one cyclone that has survived during the
249 2007-2015 time period is hindered both by the sparse sampling of the data, particularly
250 in the years 2009-2012, with very long temporal gaps with no images of the region, and
251 the relatively high zonal velocities, ranging from 60 to 95 ms^{-1} (Figure 1). In the high
252 latitudes under study, such velocities imply that a vortex can circumnavigate a whole
253 latitudinal circle in a month. More specifically, if we assume that the vortex moves with
254 the wind profile, a change of latitude of 0.1° would imply a change of velocity of 1.5 ms^{-1} .
255 If such a change of latitude occurs in a period when there are no images, the longitude
256 of the vortex could drift as much as 8° per month from the expected longitude, making
257 the identification uncertain for a typical time interval of the order of half a year.



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Figure 2: Cylindrically projected maps of the cyclonic vortex at 58.5°N. Images were captured by Cassini ISS WAC with the CB2 filter, with the exception of panel f, which corresponds to a NAC image also acquired with the CB2 filter. Dates for each panel are: (a) 13/01/2008 (b) 21/1/2009 (c) 25/7/2010 (d) 27/11/2012 (e) 17/8/2013 (f) 03/04/2014. Phase angle and pixel scale of original images are indicated in Table 1

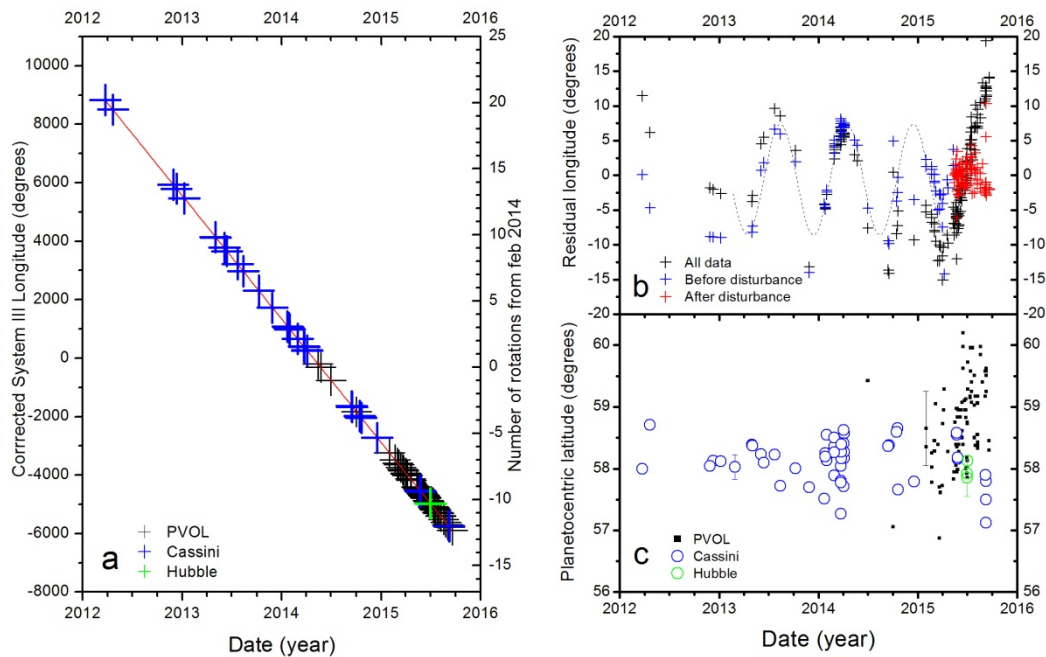
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At higher latitudes, ~60°N, in the anticyclonic region of the double peaked jet (i.e. the region to the north of the westward minimum of the zonal wind), a varying number (from 1 to 3) of similarly sized vortices are detected during the 2007-2015 period. Again, the long temporal gaps between the images make it difficult to identify uniquely any of these drifting vortices, all of very similar appearance.

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Nevertheless, at some point in 2012 the cyclone came in close contact with two anticyclones located at latitude 60°N, forming a stable triple vortex structure. This triple vortex formation is very distinct, and therefore much easier to track, particularly in the deep methane absorbing filter MT3, in which even a moderate resolution image shows the cyclone as a compact circular dark spot and the adjacent anticyclones as two bright spots. Moreover, perhaps due to the larger overall size of the ACA system combined with the higher resolution of amateur images, it was possible to detect the feature, appearing as a spot at the position of the ACA system, in amateur images from the beginning of

280 2015. We can thus continuously track the ACA system from the beginning of 2012 until
 281 at least 31st of July 2016, where its tripolar structure is apparent in very high quality
 282 amateur images available at the PVOL database.



283 **Figure 3. Panel a:** Longitudinal drift in System III of the centroid of the cyclone in the
 284 ACA system. An appropriate number of full rotations has been added to the longitude, as
 285 indicated in the axis at the right of the panel. The red line is the linear fit of the data.
 286 **Panel b:** Residuals of the linear fit to the longitude drift. In black, the residuals of the fit
 287 of all data, in blue the residuals of the fit previous to the onset of the disturbance and in
 288 red the residuals of the fit after the perturbation. The dotted sinusoidal line represents
 289 the approximate oscillations before the onset of the disturbance. **Panel c:** Latitude of the
 290 centroid of the cyclone. Typical errors in the measurements are indicated in selected
 291 points.
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293
 294 Figure 3a presents the longitude of the centroid of the cyclone at the center of the ACA
 295 system from the end of 2012 to mid-2016, tracked using Cassini ISS images taken with
 296 the MT3 and MT2 filters from 2012 to the end of 2015, amateur images from the
 297 beginning of 2015 to the end of 2015, and Hubble images from June-July 2015. Due to
 298 the fast drift rate of this feature, we present our measurements in a modified longitude
 299 system that takes into account the continuous circumnavigating motion of the feature.
 300 There are long temporal gaps in the data, but the presence of the neighboring vortices
 301 makes the identification of the cyclone certain, and the number of complete
 302 circumnavigations accounted in the modified System III longitudes in order to calculate
 303 the average drift can be unambiguously deduced because of the long temporal tracking
 304 record.

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 306 When all data are taken into account, the average planetocentric latitude of the cyclone is
 307 $58.5^{\circ} \pm 0.8^{\circ} \text{N}$ and it drifts in longitude at $-11.55^{\circ}/\text{day}$, corresponding to an average zonal
 308 velocity of $u = 69.0 \pm 1.6 \text{ ms}^{-1}$ at this latitude. Figure 3b shows the residuals from this linear
 309 fit as black points. The figure shows a clear change in the residual motion at the onset of
 310 the disturbance in May 2015. If we take into account the data up to mid May 2015 into
 311 account, the numbers are very similar (average latitude is $58.2^{\circ} \pm 0.5^{\circ} \text{N}$, and the average

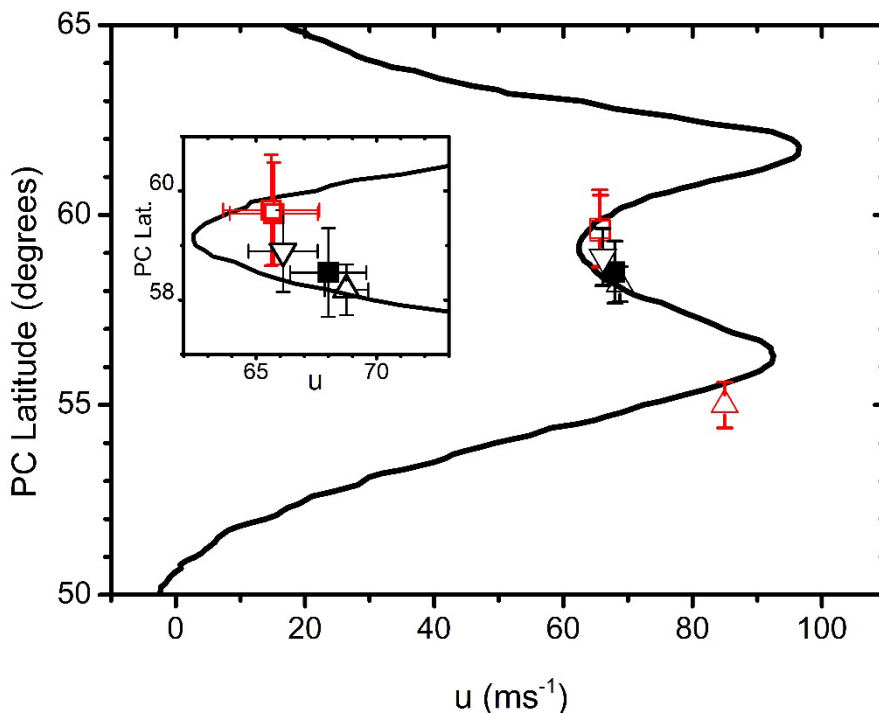
312 drift is $-11.56^\circ/\text{day}$, and corresponding a zonal velocity of $u=68.8\pm 1.0 \text{ ms}^{-1}$). The
 313 residuals of this fit are plotted in blue in Figure 3b. After the onset of the disturbance, the
 314 average latitude is $58.9^\circ\pm 0.8^\circ\text{N}$ and the longitudinal drift $11.36^\circ/\text{day}$, leading to a slight
 315 change in velocity, of $u=66.1\pm 1.5 \text{ ms}^{-1}$. We also note that, before the onset of the
 316 disturbance, the residuals of the fit show a roughly periodic behavior of amplitude $\sim 10^\circ$
 317 and a period of ~ 8 months superposed to the average zonal motion. This oscillation could
 318 be correlated with an oscillation in latitude, but the noise in the latitudinal data does not
 319 allow us to conclude whether this is indeed the case. In Figure 3c, we show the measured
 320 latitudes as a function of time, showing data points from small-size telescopes, Hubble
 321 and Cassini in different symbols. It is apparent that ground-based PVOL data after the
 322 onset of the disturbance reflect higher latitudes than data from Cassini or Hubble. This is
 323 probably an artefact due to the lower resolution of the images, which biases the latitudinal
 324 measurement toward the center of the ACA system rather than the center of the cyclone;
 325 the cyclone's latitude is always lower than those of the anticyclones (and the center of the
 326 ACA system) whenever the whole system is visible in an image.

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328 We have also tracked the longitudinal drift of the centroid of the two anticyclones using
 329 only Cassini and Hubble data. Both vortices drift at essentially the same zonal velocity.
 330 The leading anticyclone, to the east of the cyclone in the ACA system, is located at an
 331 average latitude of $59.6^\circ\pm 1.0^\circ\text{N}$ and drifts at $-11.54^\circ/\text{day}$, corresponding to an average
 332 zonal velocity of $u=65.6\pm 1.9 \text{ ms}^{-1}$, and the trailing anticyclone, to the west of the cyclone,
 333 is at the same average latitude $59.6^\circ\pm 0.9^\circ\text{N}$ and drifts at $-11.53^\circ/\text{day}$, corresponding to an
 334 average zonal velocity of $u=65.7\pm 1.9 \text{ ms}^{-1}$.

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336 Figure 4 compares the main drift rate of the vortices at different epochs with the zonal
 337 winds, showing that they are very close to the zonal wind speeds but slightly offset, and
 338 shows the small changes in the drift rate of the cyclone before and after the onset of the
 339 disturbance.



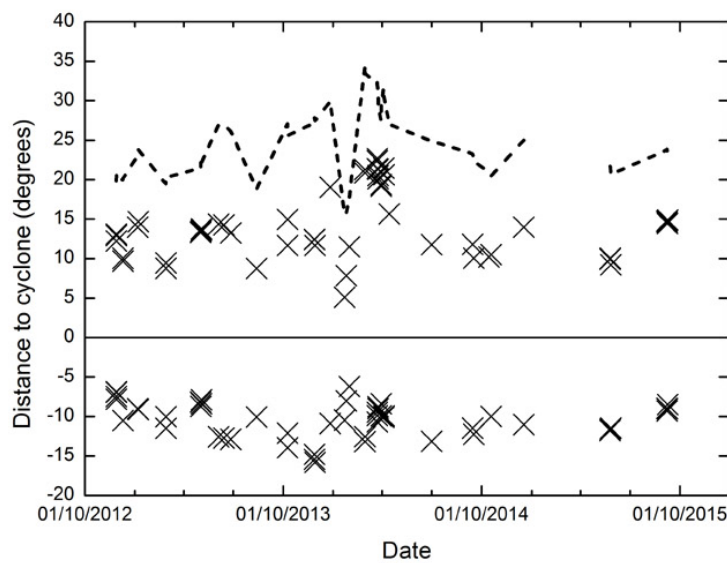
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341 **Figure 4.** Latitude and velocity of each element of the ACA system compared to Saturn's
 342 zonal wind profile. The black filled square indicates the mean latitude and velocity of the

343 cyclone (2012-2016). Upward-pointing triangle represents the average latitude and
 344 velocity before the onset of the disturbance (2012-May2015) and the downward-pointing
 345 triangle is the results after the onset of the disturbance (May-Dec 2015). The two closely
 346 placed red squares represent the average latitude and zonal drift of the two anticyclones
 347 of the ACA system and the red triangle indicates an anticyclone at 55°N that will be
 348 discussed below. Zonal wind profile is the one given in García-Melendo et al (2011).

349

350 Although the ACA system is stable, the relative separation between the vortices changes
 351 in time. Over the studied period, the longitudinal separation between the centers of the
 352 two anticyclones was on average ~25 degrees, oscillating between a minimum of 16° and
 353 a maximum of 35°. On the other hand, the location of the cyclone oscillated, alternately
 354 approaching the two anticyclones. Figure 5 shows the variation in time of the relative
 355 locations of the three vortices.



356

357 **Figure 5.** Relative distances in the ACA system. Dashed line indicates the separation
 358 between the two anticyclones between 2012 and 2015 based on Cassini ISS position
 359 measurements. The crosses represent the individual distance of the anticyclones to the
 360 cyclone placed at the continuous horizontal line at 0 degrees. The western (i.e. trailing)
 361 anticyclone is represented by the negative positions.

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363 4. Morphology and local motions of the ACA system

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365 4.1. The ACA system

366

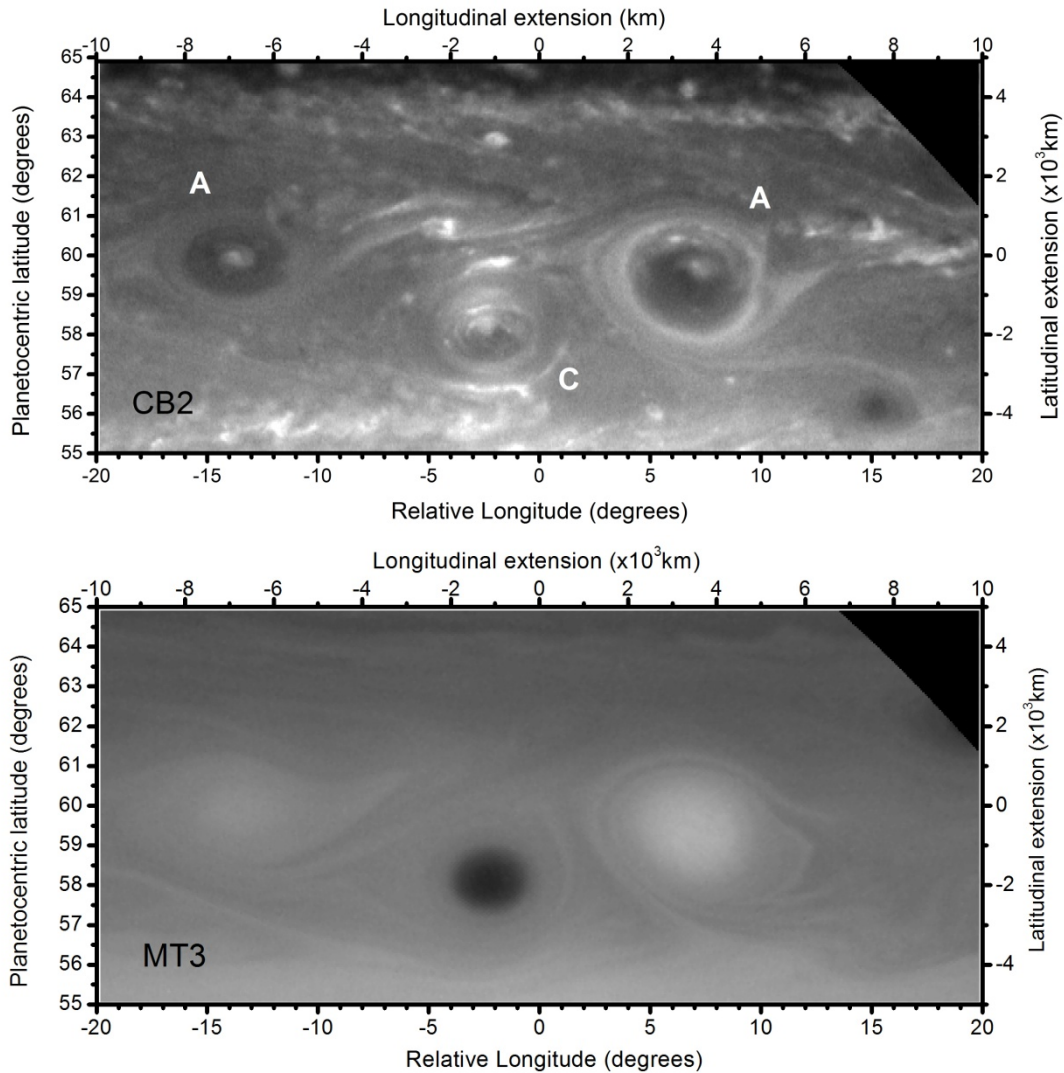
367 Figure 6 presents the appearance of the ACA system in CB2 and MT3 filters. Asay-Davis
 368 et al. (2009) showed that the sizes measured visually from the cloud appearance of Jovian
 369 vortices could be different than the dynamical sizes (as defined by the ring of maximum
 370 speed), and for example, the size of the Great Red Spot on Jupiter shrinks at different
 371 rates, depending on whether cloud appearance or dynamics is used to define the size
 372 (Simon et al. 2014). In this study, we define vortex size by cloud appearance, and
 373 uncertainties in size parameters correspond to the intrinsic spatial resolution of the Cassini
 374 and HST data. The size of the vortices that compose the system has not changed
 375 appreciably in the period of the study from the beginning of 2012 until the end of 2015.

376 In CB2 images, the cyclonic vortex extends $3.1 \pm 0.4^\circ$ in latitude and $6.8 \pm 0.5^\circ$ in longitude,
377 corresponding to an essentially circular vortex of dimensions $3,100 \pm 400$ km (North-
378 South) \times $3,400 \pm 300$ km (East-West), while in MT3 only the inner region is visible,
379 extending $1.8 \pm 0.3^\circ$ in latitude and $4.2 \pm 0.8^\circ$ in longitude, corresponding to $1,800 \pm 300$ km
380 (North-South) \times $2,100 \pm 400$ km (East-West). In all images, the anticyclonic vortex to the
381 east is larger and has a higher contrast than the anticyclone to the west. The eastern
382 anticyclone extends $2.6 \pm 0.6^\circ$ in latitude, and $6.6 \pm 1.2^\circ$ in longitude, corresponding to
383 $2,600 \pm 600$ km (North-South) \times $3,300 \pm 600$ km (East-West). The western anticyclonic
384 vortex extends $1.8 \pm 0.5^\circ$ in latitude and 4.8 ± 0.8 in longitude, corresponding to $1,800 \pm 500$
385 km (North-South) \times $2,400 \pm 400$ km (East-West).

386
387 As we have mentioned above, the system appears most conspicuous in methane
388 absorption filters MT3 and MT2. In MT3 images, the cyclonic vortex in the middle of the
389 system appears as a very compact spot dark relative to surroundings, indicating the
390 presence of a thicker layer of atmosphere above the clouds. This suggests that the clouds
391 that are visible in the continuum, possibly related to upwelling motions within the
392 cyclone, are located deeper in the atmosphere than clouds and hazes in neighboring
393 regions. This is consistent with its latitudinal location in the cyclonic region of the double
394 peaked jet. The leading and trailing anticyclonic vortices appear bright, suggesting that
395 they are structures high in the atmosphere, as expected of anticyclones, again consistent
396 with their location in the anticyclonic latitudes of the double peaked jet. We have not
397 found high-resolution images in those filters, but in moderate resolution images (Figure
398 6) the interiors of (1) the cyclone and (2) both anticyclones are essentially featureless dark
399 and bright regions respectively. This combination of a very dark compact spot surrounded
400 by two bright regions is easily recognizable, and has aided in the identification of the
401 system even in low resolution images allowing the long-time track of the system.

402
403 In the continuum filters CB2 and CB3, the contrast between the ACA system and the
404 surrounding regions is much lower, making it much harder to detect, particularly in
405 images captured in equatorial orbits, where the sub-polar region is viewed tangentially.
406 More inclined orbits allow a better view of the high-latitude region, and in Figure 6, we
407 show the appearance of the ACA system in a medium resolution image captured on
408 February 27, 2013. It shows the central cyclone as a low-contrast, slightly dark structure
409 suggestive of a vertical depression in the clouds, with numerous small white features in
410 the center, and bright clouds at the outer edge. Its visual appearance is very reminiscent
411 of that of a long-lived cyclone in the Southern hemisphere (del Río-Gaztelurrutia et al.,
412 2010). The accompanying anticyclones appear darker with a white collar surrounding
413 them and bright features in the center. The only significant changes in the appearance of
414 the ACA system in different periods are the number of bright features in the darker
415 interior of the two anticyclones.

416



417

418

419 **Figure 6.** Map projections of the ACA system in CB2 and MT3 filters. Original images
 420 were taken at a short time interval on 27 February 2013, and are labeled in the PDS
 421 database as W1740625129 (CB2) and W17406251112 (MT3).
 422

423

4.2 Local motions and vorticity.

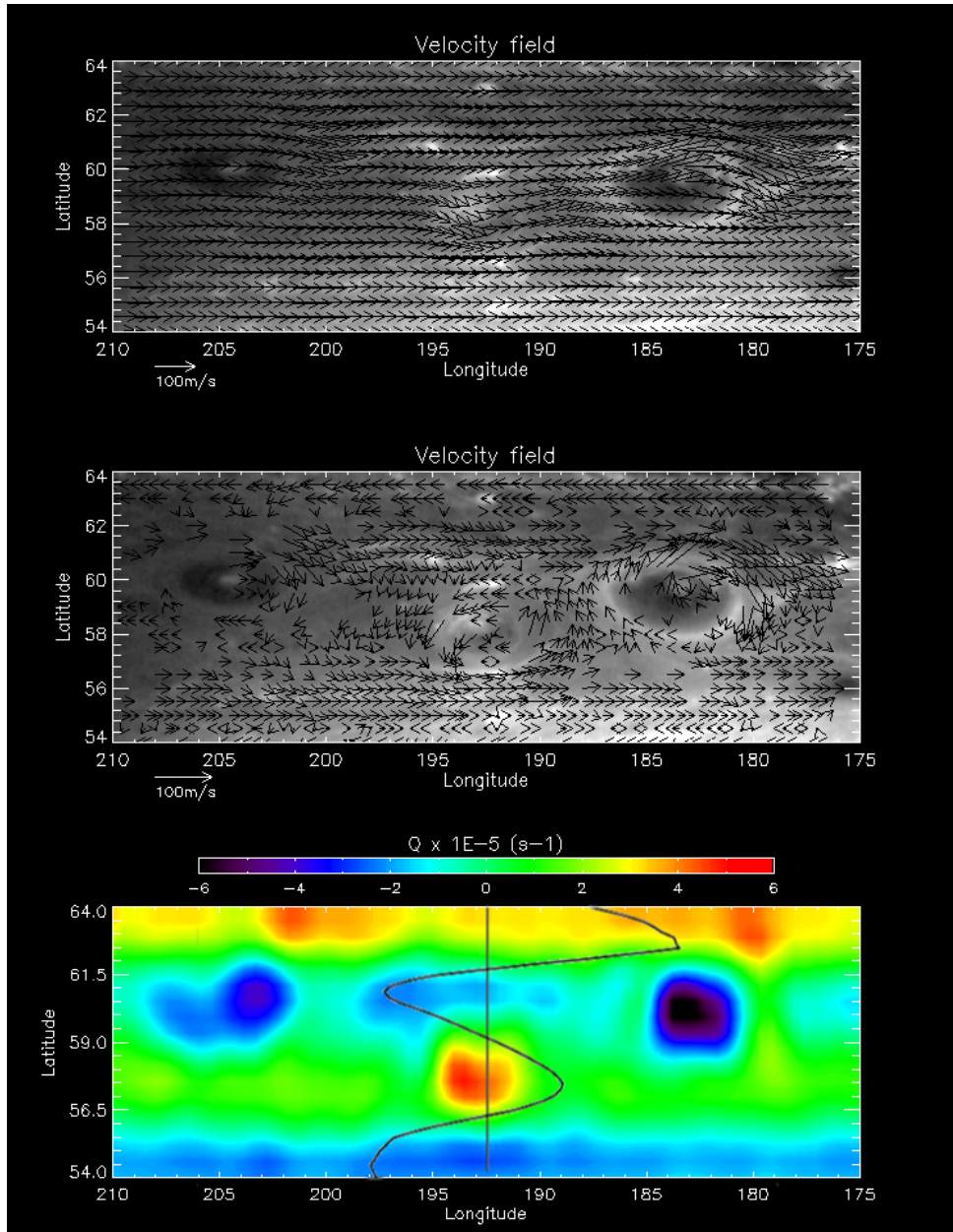
424

425 Local motions inside the ACA system have been measured using a pair of medium
 426 resolution images captured with the ISS/WAC using the CB2 filter on February 27 2013
 427 with a temporal interval of 2 hour 13 second. The original images (W1740617916 and
 428 W1740625129) have sub-spacecraft pixel scales of 36.7 km/pixel and 31.17 km/pixel,
 429 respectively. The images were projected to a resolution of 0.05°/pixel, which corresponds
 430 to a meridional spatial resolution of 25.1 km/pixel and a zonal spatial resolution of 48.7
 431 km/pixel at 59°N. The navigation is corrected via small deviations of the grid to ensure
 432 that average zonal winds outside the ACA system agree with the values past
 433 measurements by García-Melendo et al. (2011). This technique is further described in
 434 García-Melendo et al. (2011). There was a remaining uncertainty in image navigation of
 435 ± 1 pixel, leading to an error in the velocity determination of $\sim 10 \text{ ms}^{-1}$.
 436

437

438 We used the software PICV2 (Particle Image Correlation Velocimetry software written
 439 in IDL) described in Hueso et al. (2010b), to retrieve local motions. Over 3,400 vectors
 440 were derived. In order to visualize the mean flow at the ACA system and calculate
 ambient vorticity maps, the measured velocity data were interpolated to a regular grid

441 with a resolution of 0.5° . The results of this interpolation is shown in the upper panel of
 442 Figure 7, with the projection of the ACA system in the background.
 443



444
 445
 446
 447 **Figure 7.** *Upper panel* shows the interpolated local wind field at the ACA system on 27
 448 February 2013. Departures from zonal motion are apparent at the location of the cyclone
 449 and the larger anticyclone. *Middle panel* shows the local winds in the reference system
 450 of the cyclone, calculated subtracting the velocity of the centroid of the cyclone from all
 451 wind vectors, and averaged in bins of 0.5×0.5 degrees. In the **lower panel**, ambient
 452 vorticity is plotted using a color scale, with red indicating cyclonic and blue anticyclonic
 453 vorticities. The line indicates zonal ambient vorticity calculated using the zonal wind
 454 profile of García-Melendo et al. (2011), using the color bar as scale. The presence of the
 455 vortex at 58.5°N is indicated as an intensification of cyclonic vorticity, up to \sim
 456 $4.5 \times 10^{-5} \text{ s}^{-1}$. The anticyclones have maximum vorticity of $\sim -7 \times 10^{-5} \text{ s}^{-1}$ (eastern
 457 anticyclone) and $-5 \times 10^{-5} \text{ s}^{-1}$ (western anticyclone).
 458

459 Departures from zonal motion are evident in Figure 7. In order to estimate their
 460 magnitude, we have performed averages of meridional motion in longitudinal bins of
 461 0.67° (Figure 8). In the cyclonic region from 56.4°N to 59°N , we find peak values of 16 ± 9
 462 ms^{-1} , separated by $\sim 4^\circ$ in longitude, while in the anticyclonic band from 59°N to 61.8°N ,
 463 we find two oscillations, one with peak values of $36\pm 10 \text{ms}^{-1}$ separated by $\sim 5^\circ$ in longitude
 464 corresponding to the eastern anticyclone and the other with peak values of $22\pm 6 \text{ms}^{-1}$
 465 separated by $\sim 6^\circ$ corresponding to the western anticyclone.

466

467 The enhancement of vorticity in the triple vortex system becomes apparent in the
 468 reference system of the centroid of the cyclone (Figure 7, middle panel), where the eddy
 469 circulation and the interaction between the vortices is more clearly seen. A crude estimate
 470 of the increase in local vorticity $\Delta\zeta$ from the local vorticity of the zonal winds can be
 471 obtained assuming that there is a circulation superposed to the zonal motion with constant
 472 tangential velocity Δv in a circle of radius r , using the formula:

473

474

$$|\Delta\zeta| \approx \frac{2\pi r \Delta v}{\pi r^2} = \frac{2\Delta v}{r}.$$

475

476 In order to estimate $\Delta\zeta$ for the three vortices, we use the maximum north-south
 477 component of the wind from Figure 8 as an estimate for the respective vortex's tangential
 478 wind velocity v , and the east-west distance between the meridional velocity peaks as an
 479 estimate for r . For the cyclone, we find $\Delta\zeta \approx (3\pm 2)\times 10^{-5} \text{s}^{-1}$ and for the eastern and
 480 western anticyclones, we find $\Delta\zeta \approx -(5\pm 2)\times 10^{-5} \text{s}^{-1}$ and $\Delta\zeta \approx -(3\pm 2)\times 10^{-5} \text{s}^{-1}$,
 481 respectively. This simple estimation represents enhancements of vorticity over the local
 482 vorticity imposed by the meridional structure of the jet, and obviously ignores the
 483 interaction between vortices.

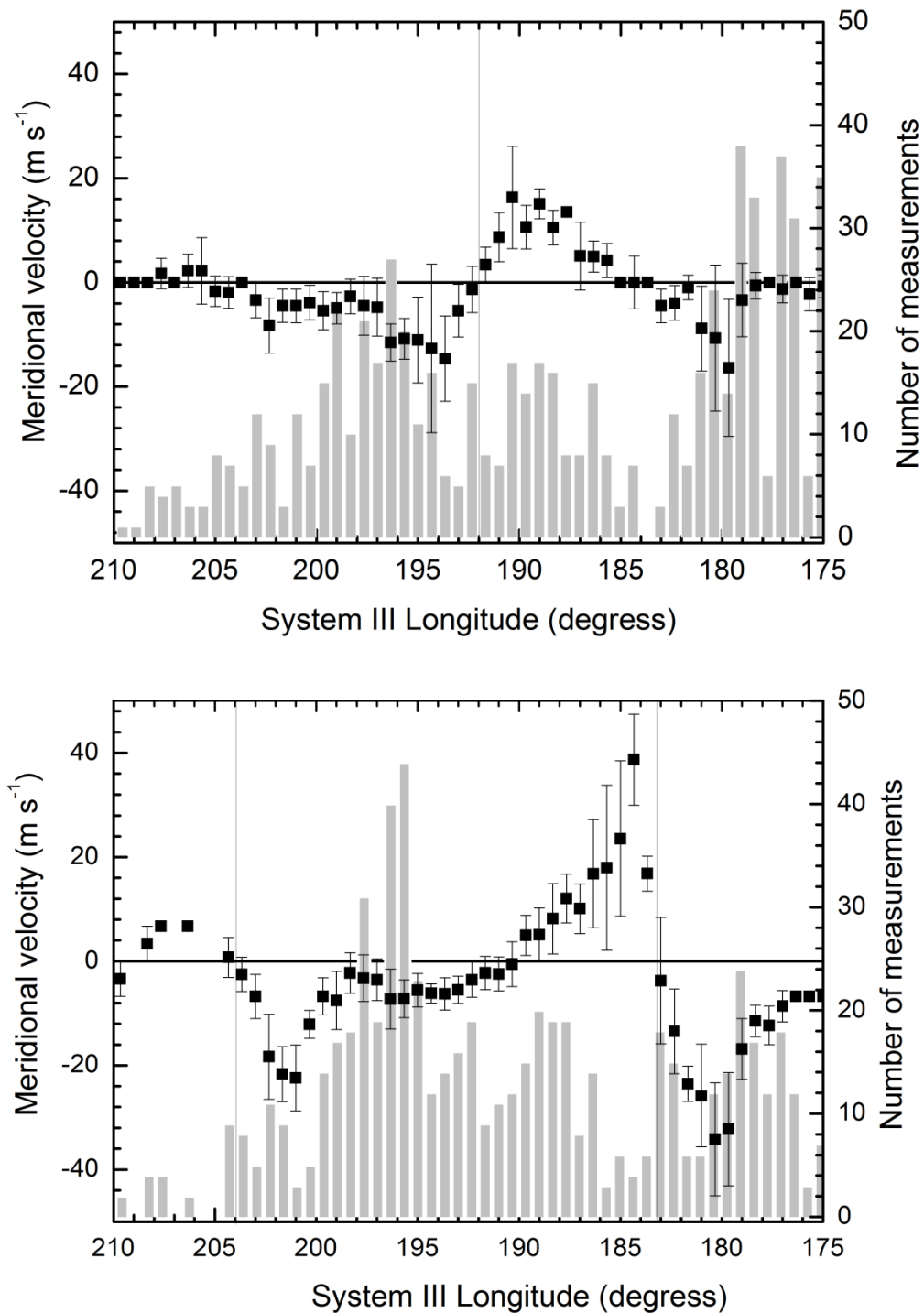
484

485 The interpolated velocity field allows us to calculate ambient vorticity maps using finite
 486 differences. The result is presented in the lower panel of Figure 7, where the line indicates
 487 zonal ambient vorticity in the region calculated from the zonal winds of García-Melendo
 488 et al. (2011), which ranges from $-2.5\times 10^{-5} \text{s}^{-1}$ to $3.9\times 10^{-5} \text{s}^{-1}$ in the region of the double-
 489 peaked jet. Even though spatially resolved maps of vorticity are noisy, the cyclonic and
 490 anticyclonic regions of the jets are retrieved in the vorticity map. At the region of the
 491 cyclone, vorticity rises from a zonal average of $1.5\times 10^{-5} \text{s}^{-1}$ to $\sim 4.5\times 10^{-5} \text{s}^{-1}$,
 492 approximately a sixth of the vertical component of planetary vorticity at the region. In the
 493 case of the anticyclones, enhancement from the zonal average of $-2.2\times 10^{-5} \text{s}^{-1}$ is higher
 494 in the anticyclone at lower longitudes, which reaches a value of total local vorticity of
 495 $\sim -7\times 10^{-5} \text{s}^{-1}$, while in the case of the anticyclone at higher longitudes, the total vorticity
 496 peaks at $\sim -5\times 10^{-5} \text{s}^{-1}$. Those results are consistent with the crude estimations of the
 497 enhancement of local vorticity given above.

498

499

500



501
 502 **Figure 8.** Meridional velocity as a function of longitude obtained from longitudinal bins
 503 of 2/3 degrees (a compromise between resolution and the number of measurements per
 504 bin). **Upper panel:** results for the cyclonic latitudinal band from 56.4°N to 59°N. **Lower**
 505 **panel:** results for the anticyclonic band from 59°N to 61.8°N, displaying the two
 506 oscillations corresponding to the two anticyclonic vortices. In both plots, error bars
 507 represent the standard deviation and the bar chart indicates the number of measurements
 508 in each longitudinal bin.

509
 510
 511

512 **5. Planetary scale disturbance**

513

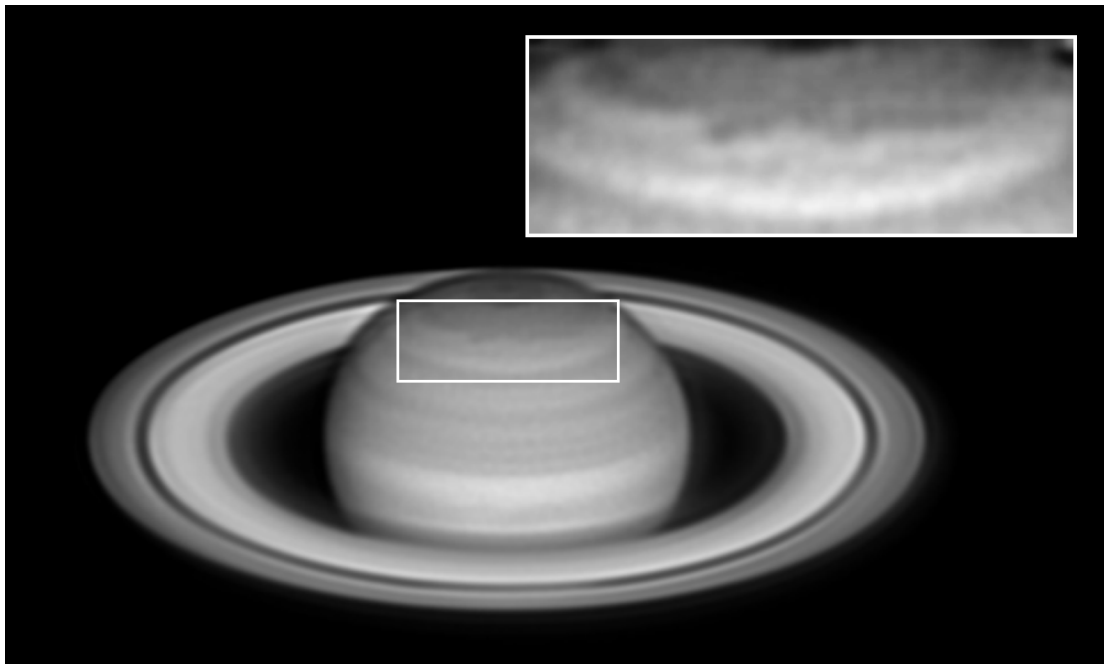
514 **5.1 Onset**

515

516 The coupling of the three vortices, together with better viewing angles of Saturn northern
517 latitudes, and recent improvements in planetary amateur astronomy techniques (Mousis
518 et al., 2014) enabled a systematic observation of the ACA system since 2014, which
519 generally appeared as a single dark spot in amateur images. On May 13, 2015, near Saturn
520 opposition, the presence of a “rift” at the location of the spot captured the attention of the
521 amateur community. Soon after, the region surrounding the spot appeared disturbed, and
522 the perturbation extended longitudinally for approximately two months, at the end of
523 which the perturbed region occupied about a third of the latitudinal circle (Figure 9).

524

525



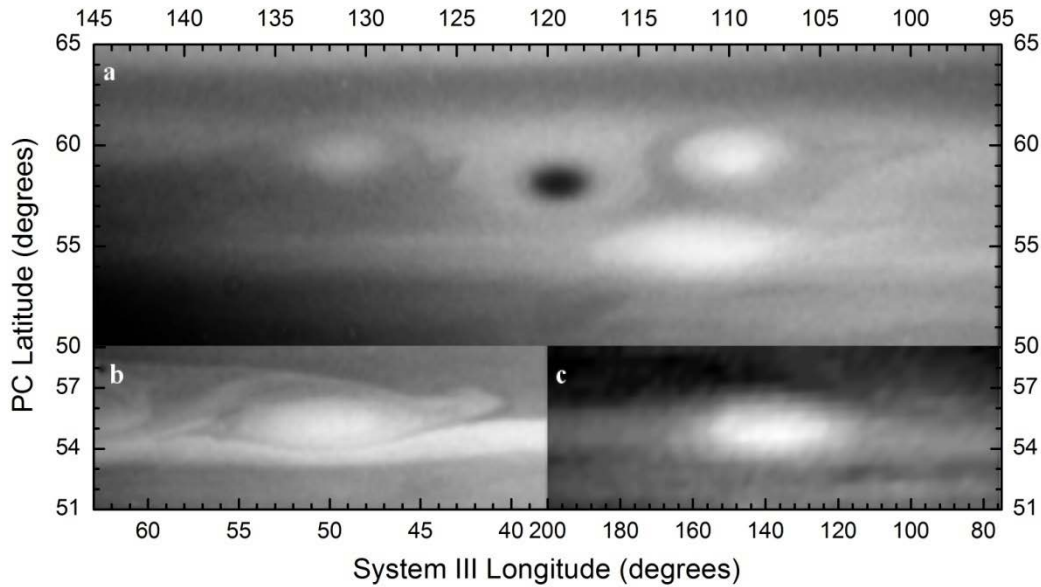
526

527

528 **Figure 9.** Image of Saturn taken by T. Barry on 15 June 2015. The inset shows a zoom
529 over the disturbed region and has been enhanced using high-pass filters. The image was
530 captured with a 16” telescope using a 685nm IR pass filter. North is up and West to the
531 left.

532

533 There is just one set of high-resolution images of the region captured by Cassini ISS near
534 the onset of the perturbation, on May 26, 2015. In these images (Figure 10a) a large vortex
535 appears south of the ACA system, at $\sim 55^\circ\text{N}$, which could be the cause of the “rift” visible
536 in amateur images. This vortex was also observed at high resolution at other dates before
537 and after the onset of the disturbance (Figure 10b and 10c). Unfortunately, the geometry
538 of Cassini ISS observations in the following months was not favorable to the observation
539 of the system, with equatorial orbits and large phase angle illumination of the planet, and
540 thus high resolution images of the region were not taken in that period.



541
 542 **Figure 10.** Map projections of the ACA system and the vortex at 55°N from images
 543 captured with the MT3 filter of Cassini ISS instrument. **Panel a:** The ACA system on 25
 544 May 2015. The vortex at 55°N is just south of the anticyclone at lower latitudes. **Panel b:**
 545 The anticyclone at 55°N on 9 February 2015. **Panel c:** The anticyclone at 55°N on 7
 546 September 2015, 79° away from the longitudinal location of the ACA system at the time,
 547 61° System III.

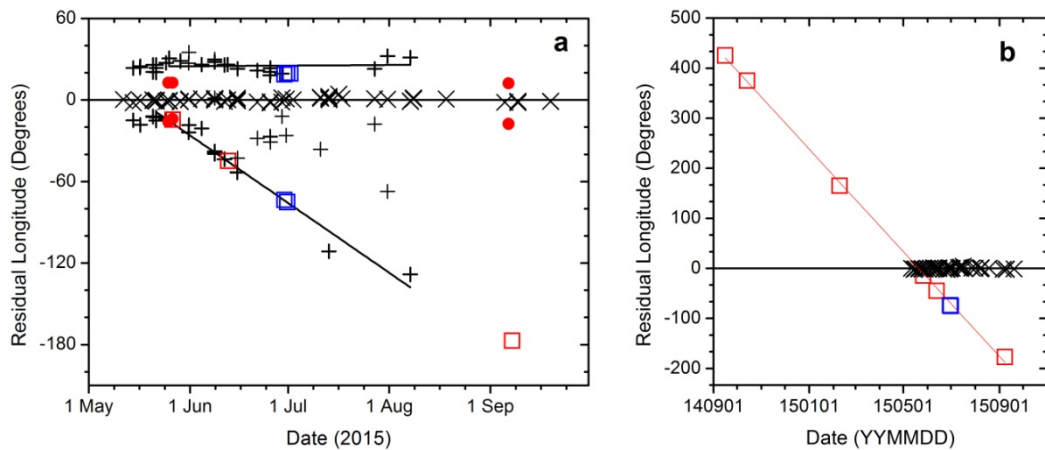
548
 549 **5.2 Zonal evolution**

550
 551 The systematic survey of the region by amateur observers allowed the study of the global
 552 evolution of the disturbance. With this aim, the position of the spot visible in amateur
 553 images (corresponding essentially to the center of the ACA system) and the limits of the
 554 disturbed region were measured on selected images obtained from the PVOL database.
 555 The average drift of the spot during the observing period (May-Sep 2015) was -
 556 11.36°/day, corresponding to $u=66 \text{ ms}^{-1}$ at its average latitude of 58.8°N.

557
 558 The longitudes of the edges of the perturbation in a reference system that moves with the
 559 spot are plotted in Figure 11a, where symbols indicate estimates of the edge of the
 560 perturbation and continuous lines represent linear fits to the best quality measurements.
 561 Figure 11a also shows the edges of the disturbed region in the high-resolution images of
 562 the region during the early period of the disturbance (HST/WFC3 observations discussed
 563 later). It is apparent from Figure 11a that the perturbation extended essentially eastwards
 564 with respect to the ACA system. The linear fit implies a mean relative drift of -1.65°/day,
 565 that is, the edge of the perturbation moved away from the ACA system at a relative
 566 velocity of $\sim 12 \text{ ms}^{-1}$.

567
 568 By mid-August, the latitudinal band had recovered an undisturbed appearance, while the
 569 spot marking the position of the ACA system remained visible.

570
 571



572
573

574 **Figure 11.** Disturbance evolution with respect to the ACA system. **Panel a:** Longitudinal
575 drift rate of the disturbance with respect to the ACA system at the time of the disturbance.
576 **Panel b:** Longitudinal drift rate of the vortex at 55°N in the reference system of the ACA
577 system for an extended period of time. In both plots, crosses indicate the residuals of
578 average drift of the centroid of the spot in amateur images during the disturbance. Blue
579 squares denote the limits of the perturbed region in HST images to be discussed later.
580 Red circles in panel a indicate the extension of the ACA system in Cassini ISS images
581 captured with the MT3 filter. Red squares represent the position of the vortex at 55.5°N.
582

583 5.3. Drift of the vortex at 55°N in the reference system of ACA

584
585 At the southern flank of the double-peaked jet, there is an anticyclonic band where
586 Trammel et al. (2016) reported the presence of several vortices. Tracking the position of
587 those vortices in time is not straightforward due to the fast zonal motions of this region,
588 long time intervals with no data, and the very similar aspect of different vortices at the
589 same latitudes.
590

591 At the time when amateurs reported “a rift” in the position of the ACA system, Cassini
592 high-resolution images show the presence of one of those vortices south of the ACA
593 system (Figure 10a). On September 6th-7th, 2015, when the disturbance had subdued, the
594 region was again visible in Cassini ISS images. The viewing conditions of the images are
595 not good, but the ACA system is clearly detected and the region east of it appears
596 unperturbed. An inspection of the full latitudinal circle on that date reveals the presence
597 of a large vortex at ~55°N (Figure 10c) at the would-be longitude of the east edge of the
598 perturbation. This suggests that the origin of the disturbance is the interaction of the ACA
599 system with an anticyclonic vortex at lower latitudes drifting faster and therefore
600 overtaking the ACA system, leaving the in-between region perturbed. In order to check
601 this hypothesis, we have searched the Cassini database in 2014-2015 for detections of
602 vortices at that latitudinal band, and plotted their longitudes in the reference system of the
603 ACA system, where their relative velocity is lower, making identification easier. We have
604 found that, indeed, the vortex can be traced back to August 2014, at an average latitude
605 of $54.8 \pm 0.3^\circ\text{N}$, approaching the ACA system at $1.70^\circ/\text{day}$ ($11.1 \pm 0.1 \text{ms}^{-1}$). The result of
606 this tracking can be seen in Figure 11b. The zonal velocity of the vortex compared with
607 the zonal winds is also indicated in Figure 4. This suggests that the disturbance observed
608 in May 2015 was due to the interaction of the 55°N vortex with the ACA system. The
609 different drift velocities of the ACA system and the vortex at 55° imply that they cross
610 each other every seven/eight months, but we have not found Cassini ISS images of the

611 region at the time of other crossings and thus we cannot confirm or exclude the possibility
612 that such an interaction occurs every crossing.

613 **5.4. Disturbance 90 days after the onset: HST images**

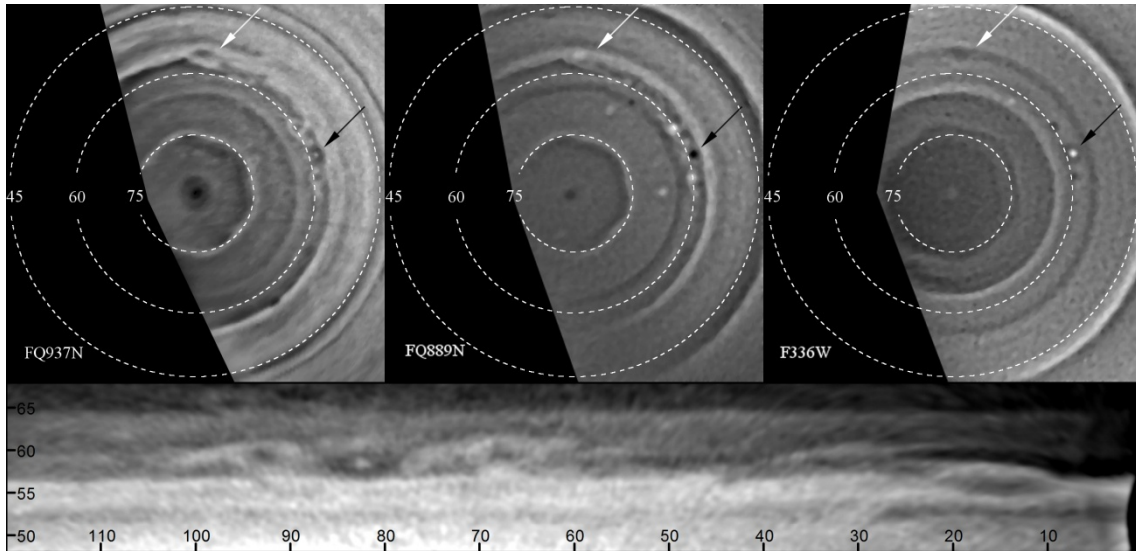
614

615 Due to the characteristics of Cassini orbits at the time, which did not allow us to observe
616 the evolution of this disturbance, we requested HST observations of Saturn. HST
617 observed Saturn on the 29th and 30th of June and the 1st of July 2015. HST WFC3 images
618 of the region were captured approximately 40 days after the start of the disturbance. There
619 are three sets of images, separated by two planetary rotations. In the first two sets,
620 captured on the 29th and 30th of June, the ACA system is essentially on the sub-Earth
621 meridian, and thus the images show the complete perturbed region. The third set, captured
622 on July 1, the ACA system is closer to the limb and the eastern limit of the perturbed area
623 is hidden from view. In Figure 12, we show three polar projections of the planet from
624 images taken with the FQ937N, F889N and F336W filters on 29 June 2015. The first two
625 filters are narrow band filters that have been chosen for their similarity to CB3 and MT3
626 filters in Cassini ISS, while the last one is a wide band filter providing images in the
627 ultraviolet.

628

629 A comparison of the three images allows us to estimate the relative height of the different
630 details and confirms that the ACA system consists of a cyclone surrounded by two
631 anticyclones. Images in F889N in the strong methane absorption band and in F336W in
632 the ultraviolet have contrasts essentially inverse of each other, with dark spots in the
633 F889N filter being bright in the ultraviolet and bright regions in the F889N filter being
634 dark in the ultraviolet. This is consistent with our interpretation of dark regions in the
635 methane filters as regions with lower clouds, and thus a thicker layer of haze that becomes
636 visible in the ultraviolet. At the eastern end of the perturbed area, a light spot in F889N
637 images, seen faintly as a slightly darker spot in the F336W filter, marks the location of
638 the anticyclone at lower latitudes ($\sim 55^\circ\text{N}$). The position of this feature is plotted as a blue
639 square in Figure 11a. The most remarkable difference between the images appears in the
640 intermediate region, which in the F336W filter is totally unperturbed, suggesting that the
641 disturbance lies in the upper cloud deck, observed in the FQ937N filter image, without
642 disturbing the hazes above the cloud (West et al., 2009). In this image, the ACA system
643 displays the same morphology as in Figure 6, albeit with lower resolution. A bright spot
644 in the cyclone is suggestive of the clouds visible in Figure 6, and the white collar of both
645 anticyclones can be clearly seen in the lower resolution images. A complete analysis of
646 these images in terms of the vertical cloud structure is undergoing and will be presented
647 elsewhere.

648



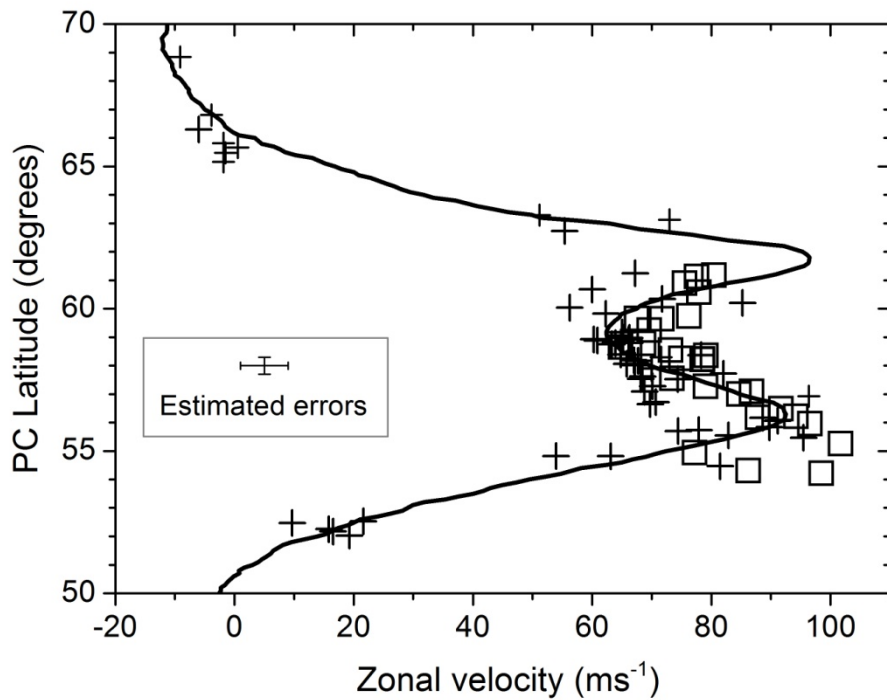
649
650

651 **Figure 12.** Polar and cylindrical projections of the polar disturbance. **Upper panels:**
652 Polar projections of HST WFC3 images of Saturn's North Polar Region taken on 30 June
653 2015. The WFC3 filter used is indicated in each panel. Black arrows indicate the position
654 of the ACA system and white arrows the vortex at 55°N. **Lower panel:** Cylindrical map
655 projection of the FQ937N image covering 20° in latitude and in 120° longitude. The 55°N
656 vortex is visible at 15° longitude and the ACA system is centered at 83° longitude.

657

658 We measured the positions of cloud features observed in each of the three HST orbits in
659 order to study the zonal motions of features of the ACA system and the disturbed region.
660 Since there are three sets of images, each separated by approximately 20 hours, and the
661 ACA system and most of the disturbed region are covered in all three sets, we have used
662 linear fits to determine the average zonal motion of each individual feature. The results
663 of this analysis in terms of zonal winds are shown in Figure 13. Features pertaining to the
664 disturbance are shown with squares and other features with plus symbols. We observe
665 that the motion of the features in the disturbance follows the average zonal wind profile
666 within the wind measurement errors. This suggests that the disturbed area is the result of
667 the advection of the cloud patterns created by the interaction of the ACA system with the
668 vortex at the south when this eastward moving faster vortex overtook the ACA system,
669 confirming that the perturbation was created by the interaction of the ACA system with
670 the vortex at 55°N.

671



672 **Figure 13.** Velocity measurements determined from cloud tracking in HST images.
 673 Squares indicate features pertaining to the disturbance of the ACA system. Plus symbols
 674 indicate all other features tracked. Measurements errors are shown in the inset.
 675

676

677

678

679 **6. Numerical models of the three-vortex system**

680 We performed numerical simulations of the ACA system to establish under what
 681 conditions it is stable. We used the Explicit Planetary Isentropic Coordinate model (EPIC)
 682 (Dowling et al., 1998) and a one-layer shallow water model (García-Melendo and
 683 Sánchez-Lavega, 2017).

684 The EPIC model is a hydrostatic multilayer model that uses potential temperature as
 685 vertical coordinate. In the model, the pressure range for the vertical domain must be
 686 specified as well as the number of layers, which determines the vertical resolution. In our
 687 study of other regions of Saturn (see e.g. García-Melendo et al., 2007; Legarreta and
 688 Sánchez-Lavega, 2008; del Río-Gaztelurrutia et al., 2010), a relatively coarse vertical
 689 resolution (8 layers in the 10 mbar to 10 bar pressure range) was sufficient to achieve
 690 numerical stability, but this proved not to be the case in the region of the ACA system.
 691 With the aid of the much faster one-layer shallow water (SW) simulations, we found that
 692 in the region of the ACA the model atmosphere was stable only for layers with depths
 693 smaller than ~ 1000 m (corresponding to barotropic Rossby radius of deformation
 694 $L_D = \sqrt{gH} / f \sim 300$ km, $L_D = \sqrt{gH} / f \sim 300$ km, where $g = 8.8$ m s $^{-1}$ is the gravity
 695 acceleration, $H \cong 1000$ m the depth of the layer, and $f \sim 3 \times 10^{-4}$ s $^{-1}$ the Coriolis parameter).
 696 This is consistent with the idea that a small barotropic radius of deformation makes the
 697 model atmosphere more stable, because it limits the characteristic size of growing
 698 instabilities. Since EPIC is also a multilayer hydrostatic model, the numerical results of
 699 the SW model also suggested that the vertical resolution in the EPIC model had to be
 700 much higher than in our previous works. To increase vertical resolution without a

701 substantial increase of computational time, we restricted our EPIC-model calculations to
702 a narrower vertical range, between 200 mbar and 500 mbar, to make sure that the top
703 cloud level was included in the model, and the vertical domain was divided in 5 layers.

704
705 Morales-Juberías et al. (2010) used EPIC to study the mergers between the spots of the
706 South-South Temperate Zone (SSTZ) of Jupiter. Their results indicate that the vortices
707 on the SSTZ were less prone to merge for high values of the vertical static stability. The
708 coexistence of local convective storms and vortices suggest that the actual value of the
709 static stability in Saturn's upper cloud deck can vary significantly in relatively short
710 distances (García-Melendo et al., 2007), and thus, in our EPIC model, and over the entire
711 simulation domain, we assumed a simple vertical structure with a ~~high~~ constant static
712 stability with Brunt-Väisälä frequency $N^2 = 0.6 \times 10^{-4} \text{s}^{-2}$. The exploration of lower
713 values, down to $N^2 = 0.1 \times 10^{-4} \text{s}^{-2}$ did not lead to substantial differences. On the other
714 hand, the use of the thermal wind equation from CASSINI/CIRS data shows that, at high
715 latitudes, the vertical shear is negligible between 200 mbar and 500 mbar. (García-
716 Melendo et al. 2011). Therefore, we used the zonal wind of García-Melendo et al. (2011)
717 with no vertical shear. Under such conditions, the baroclinic Rossby deformation radius
718 estimated from the vertical static stability of the model atmosphere is $L_D = NH/f \sim 2,300$
719 km, similar to the size of the vortices.

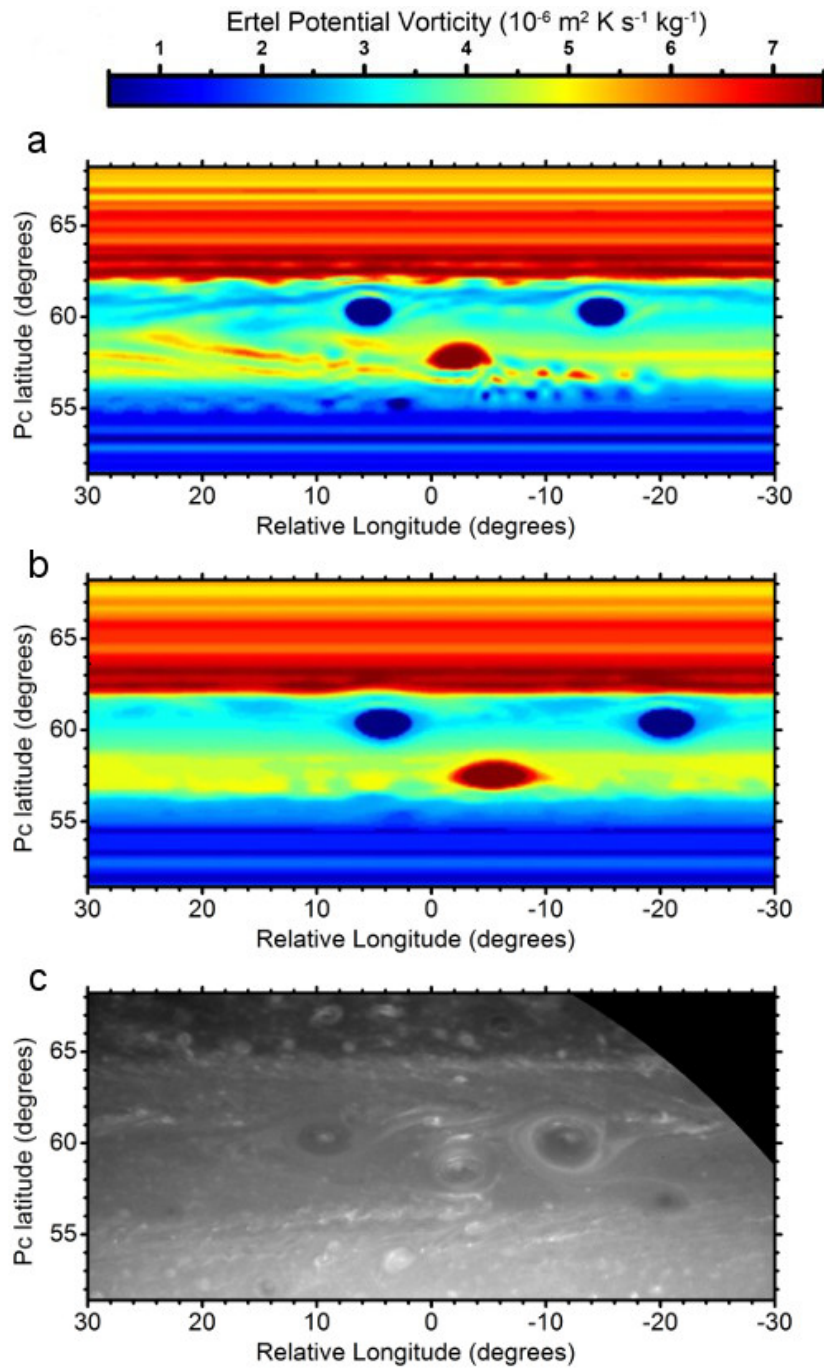
720 Our simulations were run in a channel 60 degree-long between the planetographic
721 latitudes of 57°N and 72°N, (corresponding to planetocentric latitudes from 51.2°N to
722 68.1°N) at a grid resolution of 0.12 degrees grid⁻¹. Boundary conditions in the EPIC model
723 were full slip conditions for the limiting latitudes of the channel, periodic boundary
724 conditions for limiting longitudes, and no heat transfer in the limiting vertical boundaries
725 (Dowling et al., 1998). Vortices were introduced as Gaussian-shaped, geostrophically
726 balanced perturbations in the Montgomery potential field. All the vortices had a zonal
727 length of 3.5°, a meridional extent of 1.5° and tangential velocity at periphery of 50 ms⁻¹
728 It is generally agreed (Legarreta and Sánchez-Lavega, 2008) that vortices in Jupiter and
729 Saturn are thin relative to their horizontal size and to the thickness of the deep atmosphere,
730 with vertical spans between 2 and 4 scale heights. In our case, computational constraints
731 limited our vertical domain to ~1 scale-height, and therefore in our simulations the
732 vortices extended through the whole vertical domain.

733 The zonal wind domain where the vortices live is very narrow, with cyclonic and
734 anticyclonic bands ~2.5° wide. There is therefore little margin to fit vortices at different
735 latitudes if their sizes are comparable to the size of the vorticity domains where they sit
736 (see inset in Figure 1). The best latitudes to reproduce a stable ACA system are 58° for
737 the center of the cyclone and 60° for the centers of the anticyclones, very similar to the
738 measured values for the real vortices. At these latitudes, the three-vortex configuration
739 remained stable for at least 100 days. For other latitudes, it was not possible to adjust drift
740 velocities for the vortices to obtain a compact stable system for such a long time span, or
741 the vortices themselves were not stable as they protruded too deeply into regions of
742 opposite vorticity. Figure 14 shows potential vorticity maps of the ACA system after 15
743 and 95 days respectively of simulation time.

744 In addition to constraining the parameters of the EPIC simulations, shallow water models
745 simulated the interaction between the cyclone and the anticyclones as a relative
746 oscillatory movement of the cyclone with respect to the anticyclones (Figure 15), hints of
747 which can be noticed in Figure 5. This behavior reproduces the well-known result that
748 vortices embedded in a sheared background zonal flow with opposite vorticity repel when
749 they come close enough (Youssef and Marcus, 2003.)

750

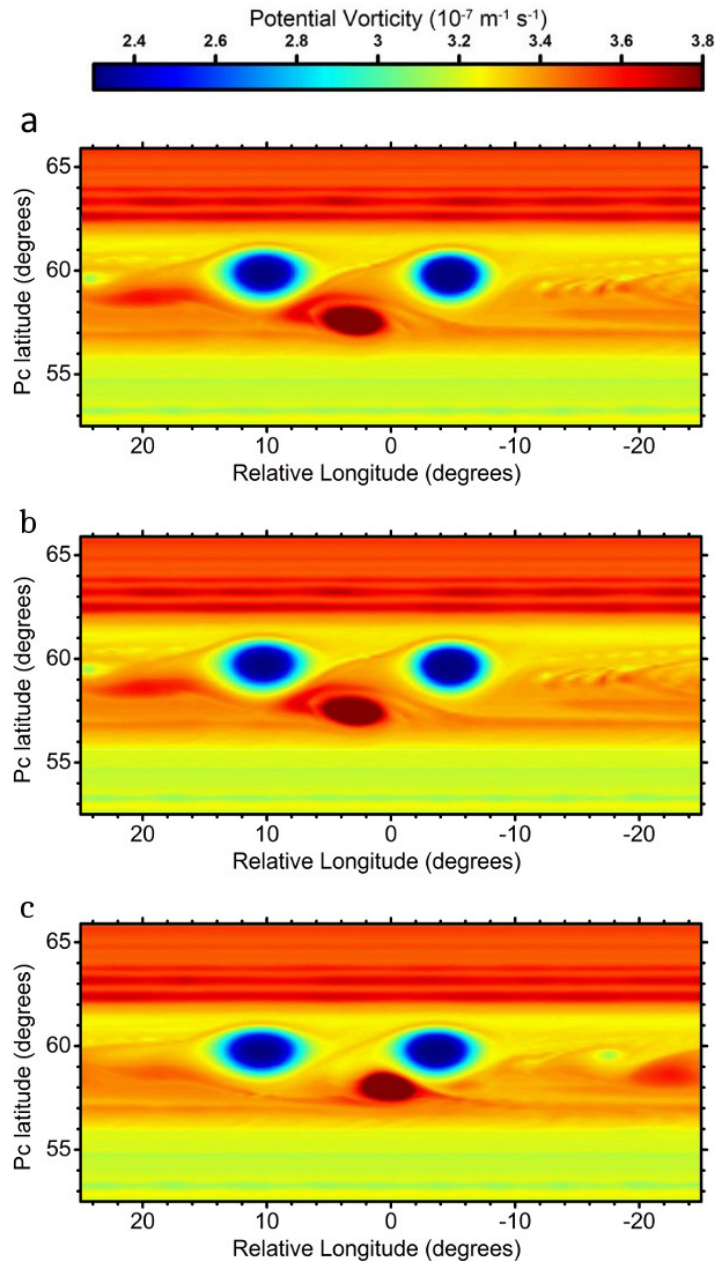
751



752

753 **Figure 14.** Ertel potential vorticity maps at the 340 mbar level after EPIC simulations of
754 the ACA system after 10 days (A), and 100 days (B). Panel C shows the ACA system on
755 27 Feb 2013 for comparison.

756



757

758 **Figure 15.** Potential vorticity maps of shallow water simulations showing oscillations of
 759 the cyclonic vortex between the anticyclones for (A) 20 days, (B) 30 days, and (C) 45 days
 760 simulation times. The model consisted in a channel with a Rossby radius of deformation
 761 of ~ 300 km. Resolution was of 0.25 degrees pixel^{-1} .

762 The mechanism for the long stability and robustness of the ACA system remains unclear.
 763 Youssef and Marcus (2003), in their analysis of the Jovian white ovals merger, found that
 764 an ACA system of stable vortices could be maintained by a Rossby wave formed in a
 765 region of sharp gradient of background potential vorticity, with the anticyclones trapped
 766 in the troughs of the wave. They argued that the Jovian white ovals merger and end of the
 767 Jovian ACA system occurred due to “hops” of the cyclone and one anticyclone, possible
 768 if the approach velocity of the two vortices is sufficiently large to overcome the repulsion.
 769 Sanchez-Lavega et al. (2001) argued that the encounter and interaction of the Great Red
 770 Spot (northward of the system) and the Jovian ACA (first BC-C-DE, then BE-C-FA, to
 771 form finally BA), displaced in latitude the central cyclone favoring the two anticyclone
 772 merger. In the case of the Saturnian ACA system, the vortices are embedded in a similar

773 vorticity background, although the jet configuration is different (Figure 4). In our
774 simulation experiments, no clear Rossby wave trap was formed in the potential vorticity
775 field, as anticyclones always drifted away from each other in long-term simulations. We
776 propose that the passage of the large anticyclone located south of the ACA system, which
777 could resemble the interaction of the GRS with the white ovals, because of the different
778 jet structure instead of displacing the cyclone, triggered a disturbance. A detailed study
779 on this complex “four-vortex interaction” is under development and will be presented
780 elsewhere.

781

782 **7. Summary and conclusions**

783

784 In this paper, we have described a singular long-lived vortex system in the northern
785 subpolar latitudes of Saturn and a disturbance surrounding this region that developed in
786 mid May 2015. Our main conclusions are:

787

788 • We have characterized a triple vortex system formed by a cyclone and two
789 anticyclones, here nicknamed ACA. This system is unique in Saturn and is located in
790 the double-peaked eastward jet at 56°-62°N planetocentric latitudes. The singular
791 structure of the jet, with two very close regions of opposite vorticities moving at a fast
792 velocity seems to favor the stability of this triple structure. This could be due to the
793 beta effect (Holton, 2004; Sayanagi et al., 2013), that favors a drift to the north for the
794 cyclone and to the south for the anticyclones.

795

796 • The ACA system has been tracked unambiguously since 2012, and it is still present
797 in images of Saturn at the time of this writing. The system shows a stable motion
798 consistent with the wind profile, with oscillations of $\sim 10^\circ$ relative to its average
799 motion with a period of ~ 4 months.

800

801 • Vortices in Saturn can be long lived, surviving for periods of several years. Here, we
802 have demonstrated the survival of a cyclone and its surrounding anticyclones for at
803 least four years, confirming our results of a previous paper in which we found the
804 survival of a similar vortex in the Southern Hemisphere of the planet (del Río-
805 Gaztelurrutia et al., 2010). It is quite likely that the lifetime of the cyclone at the ACA
806 system is even longer, but we have not been able to confirm unequivocally that the
807 single cyclonic vortex detected at $\sim 58^\circ\text{N}$ from 2009 to 2012 is the same cyclone that
808 forms part of the ACA system.

809

810 • We have confirmed the cyclonic and anticyclonic vorticities of these vortices by
811 tracking small clouds motions. The relative vorticity of the cyclone is enhanced to a
812 total value of $\sim 4.5 \times 10^{-5} \text{ s}^{-1}$, approximately three times the ambient vorticity due to
813 the jet structure. The total relative vorticity of the anticyclones is $\sim 7 \times 10^{-5} \text{ s}^{-1}$ and
814 $\sim 5 \times 10^{-5} \text{ s}^{-1}$, 2-3 times the ambient vorticity of the region.

815

816 • We have analyzed a disturbance that was detected from ground-based telescopes in
817 mid-May 2015. This disturbance is related to the interaction of the ACA system with
818 a large anticyclonic vortex at lower latitudes (55°N), moving faster than the ACA
819 system and thus overtaking it. We have tracked the motion of this vortex in the
820 reference system of the ACA, which allows unmistakable detection of the three-
821 vortex system despite the very fast motion of the vortices and the scarcity of data with
822 long time gaps. We have shown that the growth of the disturbance followed the
823 motion of the vortex once it overtook the ACA system. Our tracking of the vortex at

824 55° further confirms that lifetime of vortices in Saturn can be significantly larger than
825 a year.

826

827 • HST images have enabled us to study the local motions at the time of the polar
828 disturbance formed by the interactions of these vortices. The analysis reveals that, in
829 spite of the large morphological changes associated with the disturbance, the features
830 in the region move consistently with the average zonal wind profile. This shows that
831 the clouds created by the interaction or the ACA system with the vortex at its south
832 were essentially advected by the local winds creating a perturbed region without the
833 need for introducing further dynamical mechanisms such as local convection.

834

835 • In a numerical model, a stable three-vortex system can be reproduced for a ~100 day
836 time span only when vortices are simulated at the same latitudes as those measured
837 for the real vortices, but it is still unclear what mechanism makes the ACA system a
838 compact stable structure.

839

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841

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854 **References**

855

856 Archinal, B.A., A'Hearn, M.F., Bowell, E., Conrad, A., Consolmagno, G.J., Courtin, R.,
857 Fukushima, T., Hestroffer, D., Hilton, J.L., Krasinsky, G.A., Neumann, G., Oberst, J.,
858 Seidelmann, P.K., Stooke, P., Tholen, D.J., Thomas, P.C., Williams, I.P., 2011. Report
859 of the IAU/IAG working group on cartographic coordinates and rotational elements:
860 2009. *Celestial Mech. Dyn. Astron.* 109, 101-135.

861

862 Asay-Davis, X.S., Marcus, P. S., Wong, M.H., de Pater, I., 2009. Jupiter's shrinking Great
863 Red Spot and steady Oval BA: Velocity measurements with the 'Advection Corrected
864 Correlation Image Velocimetry' automated cloud-tracking method. *Icarus* 203, 164-188.
865 doi:10.1016/j.icarus.2009.05.001.

866

867 Baines K.H., Delitsky, M.L., Momary., T.W., Brown, R.H. Robert H., Buratti, B.J., Clark,
868 R.N., Nicholson, P.D., 2009. Storm clouds on Saturn: Lightning-induced chemistry and
869 associated materials consistent with Cassini/VIMS spectra. *Planet. Space Sci.* 57, 1650-
870 1658. doi:10.1016/j.pss.2009.06.025.

871 Del Genio, A.D., Achterberg, R.K., Baines, K.H., Flasar, F.M., Read, P.L., Sánchez-
872 Lavega, A. Showman, A.P., 2009. Saturn Atmospheric Structure and Dynamics. Chapter
873 6 in: *Saturn from Cassini-Huygens*. M. Dougherty, L. Esposito and T. Krimigis (edt.),
874 Springer-Verlag, 113-159.

875 Dowling, T.E., Fischer, A.S., Gierasch, P.J., Harrington, J., LeBeau, R.P. Jr., Santori,
876 C.M., 1998. The explicit planetary isentropic-coordinate (EPIC) atmospheric model.
877 *Icarus* 132, 221-238. doi:10.1006/icar.1998.5917.

878 Dyudina, U.A., Ingersoll, A.P., Ewald, S.P., Porco, C.C., Fischer, G., Kurth, W., Desch,
879 M., Del Genio, A., Barbara, J., Ferrier J., 2007. Lightning storms on Saturn observed by
880 Cassini ISS and RPWS during 2004-2006. *Icarus* 190, 545-555,
881 doi:10.1016/j.icarus.2007.03.035.

882 García-Melendo, E., Sánchez-Lavega, A., 2001. A Study of the Stability of Jovian Zonal
883 Winds from HST Images: 1995-2000. *Icarus* 152, 316-330. doi:10.1006/icar.2001.6646.

884 García-Melendo, E., Sánchez-Lavega, A., Hueso, R., 2007. Numerical models of Saturn's
885 long-lived anticyclones. *Icarus* 191, 665-677. doi: 10.1016/j.icarus.2007.05.020.

886 García-Melendo, E., Pérez-Hoyos, S., Sánchez-Lavega, Hueso, R., 2011. Saturn's zonal
887 wind profile in 2004-2009 from Cassini ISS images and its long-term variability. *Icarus*
888 215, 62-74. doi: 10.1016/j.icarus.2011.07.005.

889 García-Melendo, E., Sánchez-Lavega, A., 2017. Shallow water simulations of Saturn's
890 giant storms at different latitudes. *Icarus* 286, 241-260. doi: 10.1016/j.icarus.2016.10.006.

891 Holton, J. R. (2004). *An Introduction to Dynamic Meteorology*, 4th ed., Academic Press,
892 San Diego, California.

893 Hueso, R., Legarreta, J., García-Melendo, E., Sánchez-Lavega, A., Pérez-Hoyos, S.,
894 2009. The Jovian anticyclone BA: II. Circulation and interaction with the zonal jets.
895 *Icarus* 203, 499–515. doi: 10.1016/j.icarus.2009.05.004.

896 Hueso, R., Legarreta, J., Perez-Hoyos, S., Rojas, J.F., Sanchez-Lavega, A., Morgado, A.,
897 2010a. The international outer planets watch atmospheres node database of giant-planet
898 images. *Planet. Space Sci.* 58, 1152-1159. doi:10.1016/j.pss.2010.04.006.

899 Hueso, R., Legarreta, J., Rojas, J.F., Pérez-Hoyos, S., del Río-Gaztelurrutia, T., Sánchez-
900 Lavega, A., 2010b. The Planetary Laboratory for Image Analysis (PLIA). *Adv. Space*
901 *Res.* 6, 1120-1138. doi: 10.1016/j.asr.2010.05.016.

902 Hueso R., Juaristi, J., Legarreta, J., Sánchez-Lavega, A., Rojas, J. F., Erard, S., Cecconi,
903 B., Pierre Le Sidaner, 2017. The Planetary Virtual Observatory and Laboratory (PVOL)
904 and its integration into the Virtual European Solar and Planetary Access (VESPA). *Planet.*
905 *Space Sci.* (in the press), doi:10.1016/j.pss.2017.03.014.

906

907 Ingersoll, A.P., Beebe, R. F., Conrath, B.J., Hunt, G.E., 1984. Structure and dynamics of
908 Saturn's atmosphere, in *Saturn*, T. Gehrels and M. S. Matthews (eds.), University of
909 Arizona press, Tucson, 195 – 238.

910

911 Ingersoll A.P., Dowling, T.E., Gierasch, P.J., Orton, G.S., Read, P.L., Sanchez-Lavega,
912 A., Showman, A.P., Simon-Miller, A.A., Vasavada A.R., 2004. Dynamics of Jupiter's
913 Atmosphere. Chp. 6 in *Jupiter: The Planet, Satellites & Magnetosphere* (Bagenal, F.,
914 McKinnon, W., Dowling T., Editors), Cambridge University Press, pp 105-128.

915

916 Legarreta J.J., Sánchez-Lavega, A., 2008. Vertical structure of Jupiter's troposphere from
917 nonlinear simulations of long-lived vortices. *Icarus* 194, 184-201. doi:
918 10.1016/j.icarus.2008.02.018.

919

920 Li, L., Ingersoll, A.P., Vasavada, A.R., Porco, C.C., Del Genio, A.D., Ewald, S.P., 2004.
921 Life cycles of spots on Jupiter from Cassini images. *Icarus* 172, 9-23. doi:
922 10.1016/j.icarus.2003.10.015.
923

924 Lii, P.S., Wong, M.H., de Pater, I., 2010. Temporal variation of the tropospheric cloud
925 and haze in the Jovian equatorial zone. *Icarus* 209, 591-601. doi:
926 10.1016/j.icarus.2010.05.021.
927

928 Marcus, P.S., X. Asay-Davis, M.H. Wong, de Pater, I., 2013. Jupiter's New Red Oval:
929 Dynamics, Color, and Relationship to Jovian Climate Change. *Journal of Heat Transfer*
930 135, 011007-1 to 011007-9. doi:10.1115/1.4007666.
931

932 Morales-Juberías, R., Brindle, E.S., Dowling, T.E., 2010. Jupiter's South South
933 Temperate Zone vortices: Observations and simulations. *Icarus* 206, 747-754. doi:
934 10.1016/j.icarus.2009.10.002.
935

936 Mousis, O., and 59 coauthors, 2014. Instrumental Methods for Professional and Amateur
937 Collaborations in Planetary Astronomy. *Experimental Astronomy* 38, 91-191. doi:
938 10.1007/s10686-014-9379-0.
939

940 de Pater, I., Wong, M. H., Marcus, P.S., Luszcz-Cook, S., Ádámkóvics, M., Conrad, A.,
941 Asay-Davis, X., Go, C., 2010 Persistent Rings in and around Jupiter's Anticyclones -
942 Observations and Theory. *Icarus* 210, 742-762. doi: 10.1016/j.icarus.2010.07.027.
943

944 Porco, C.C., West, R.A., McEwen, A., Del Genio, A.D., Ingersoll, A. P., Thomas, P.,
945 Squyres, S., Dones, L., Murray, C.D., Johnson, T.V., Burns, J. A., Brahic, A., Neukum,
946 G., Veverka, J., Barbara, J.M., Denk, T., Evans, M., Ferrier, J.J., Geissler, P., Helfenstein,
947 P., Roatsch, T., Throop, H., Tiscareno, M., Vasavada, A.R. 2003. Cassini imaging of
948 Jupiter's atmosphere, Satellites and Rings. *Science* 299 (5612), 1541-1547. doi:
949 10.1126/science.1079462.

950

951 Porco, C.C., West, R.A., Squyres, S., Mcewen, A., Thomas, P., Murray, C.D., Delgenio,
952 A., Ingersoll, A.P., Johnson, T.V., Neukum, G. J. Veverka., Dones, L., Brahic, A., Burns,
953 J.A., Haemmerle, V., Knowles, B., Dawson, D., Roatsch, T., Beurle, K., Owen, W.
954 (2004). Cassini imaging science: Instrument characteristics and anticipated scientific
955 investigations at Saturn. *Space Sci. Rev.* 115, 363–497. doi: 10.1007/s11214-004-1456-
956 7.
957

958 del Río-Gaztelurrutia, T., Legarreta, J., Hueso, R., Pérez-Hoyos, S., Sánchez-Lavega, A.,
959 2010. A long-lived cyclone in Saturn's atmosphere: observations and models. *Icarus* 209,
960 665-681. doi: 10.1016/j.icarus.2010.04.002.

961 Rogers, J.H. (1995) "The Giant Planet Jupiter" Cambridge University Press

962 Sánchez-Lavega, A., Lecacheux, J., Colas, F., Laques, P., 1993. Ground-Based
963 observations of Saturn's North Polar Spot and Hexagon. *Science* 260, 329-332. doi:
964 10.1126/science.260.5106.329.

965 Sánchez Lavega,A., Rojas, J. F., Acarreta, J. R., Lecacheux, J., Colas, F., Sada, P.V.,
966 1997. New Observations and studies of Saturn's long-lived North Polar Spot. *Icarus* 128,
967 322-334. doi: 10.1006/icar.1997.5761.
968

969 Sánchez Lavega, A., Rojas, J.F., Hueso, R., Lecacheux, J., Colas, F., Acarreta, J.R.,
970 Miyazaki, I., Parker, D.C., 1999. Interaction of Jovian White Ovals BC and DE in 1998
971 from Earth-Based Observations in the visual range, *Icarus* 142, 116 – 124. doi:
972 10.1006/icar.1999.6197.
973
974 Sánchez-Lavega, A., Rojas, J.F., Sada, P.V., 2000. Saturn's zonal winds at cloud level.
975 *Icarus* 147, 405-420. doi: 10.1006/icar.2000.6449.
976
977 Sánchez-Lavega, A., Orton, G.S., Morales, R., Lecacheux, J., Colas, F., Fisher, B.,
978 Fukumura-Sawada, P., Golisch, W., Griep, D., Kaminski, C., Baines, K., Rages, K., West,
979 R., 2001. The merger of two giant anticyclones in the atmosphere of Jupiter. *Icarus* 149,
980 491-495. doi:10.1006/icar.2000.6548.
981
982 Sánchez-Lavega A., Pérez-Hoyos, S., Rojas, J. F., Hueso, R., French R. G., 2003. A
983 strong decrease in Saturn's equatorial jet at cloud level. *Nature* 423, 623-625.
984 doi:10.1038/nature01653.
985
986 Sánchez-Lavega A., Hueso, R., Pérez-Hoyos, S., Rojas, J. F., French. R. G., 2004.
987 Saturn's Cloud Morphology and Zonal Winds before the Cassini Encounter. *Icarus* 170,
988 519-523. doi: 10.1016/j.icarus.2004.05.002.
989
990 Sánchez-Lavega, A., 2005. How long is the day on Saturn? *Science* 307, 1223–1224.
991 doi:10.1126/science.1104956.
992
993 Sánchez-Lavega A., del Río-Gaztelurrutia, T., Delcroix, M., Legarreta, J.J., Gómez-
994 Forrellad, J. M., Hueso, R., García-Melendo, E., Pérez-Hoyos, S., Barrado-Navascués,
995 D., Lillo J., 2012. Ground-based Observations of the Long-term Evolution and Dead of
996 Saturn's 2010 Great White Spot. *Icarus* 220, 561-576. doi:10.1016/j.icarus.2012.05.033.
997
998 Sanchez-Lavega, A., García-Melendo, E., Perez-Hoyos, S., Hueso, R., Wong, M. H.,
999 Simon, A. A., Sanz-Requena, J. F., Antuñano, A., Barrado-Izagirre, N., Garate-Lopez, I.,
1000 Rojas, J. F., del Rio Gaztelurrutia, T., Gómez-Forrellad, J. M., de Pater, I., Li, L. Barry,
1001 T. and PVOL contributors, 2016. An Enduring rapidly moving storm as a guide to
1002 Saturn's equatorial jet complex structure. *Nature Communications* 7: 13262. doi:
1003 10.1038/ncomms13262.
1004
1005 Sayanagi, K.M., Dyudina, U.A., Ewald, S.P., Fischer, G., Ingersoll, A.P., Kurth, W. S.,
1006 Muro, G.D., Porco, C.C., West, R.A., 2013 Dynamics of Saturn's great storm of 2010-
1007 2011 from Cassini ISS and RPWS. *Icarus* 223, 460-478.
1008 doi:10.1016/j.icarus.2012.12.013.
1009
1010 Sayanagi, K.M., Dyudina, U.A., Ewald, S.P., Muro, G.D., Ingersoll, A.P., 2014. Cassini
1011 ISS observation of Saturn's String of Pearls. *Icarus* 229, 170-180. doi:
1012 10.1016/j.icarus.2013.10.032.
1013
1014 Simon, A.A., Beebe, R.F., 1996. Jovian Tropospheric Features—Wind Field,
1015 Morphology, and Motion of Long-Lived Systems. *Icarus* 121, 319-330. doi:
1016 10.1006/icar.1996.0090.
1017
1018 Simon, A.A., Wong, M.H., Rogers, J.H., Orton, G.S., de Pater, I., Asay-Davis, X.,
Carlson, R.W., Marcus, P.S., 2014. Dramatic change in Jupiter's Great Red Spot from

- 1019 spacecraft observations. *Astrophysical Journal Letters* 797, L31-L34. doi:10.1088/2041-
1020 8205/797/2/L31.
- 1021 Simon, A. A., Wong, M. H., Orton, G. S., 2015. First results from the Hubble OPAL
1022 Program: Jupiter in 2015. *The Astrophysical Journal* 815:55, 8 pp. doi:10.1088/0004-
1023 637X/812/1/55.
- 1024
- 1025 Smith, B.A, and 25 co-authors, 1981. Encounter with Saturn: Voyager 1 imaging results.
1026 *Science* 212, pp.163-191. doi: 10.1126/science.212.4491.163.
- 1027
- 1028 Smith, B.A, and 28 co-authors, 1982. A new look at the Saturn system: The Voyager 2
1029 images. *Science* 215, pp.505-537. doi:10.1126/science.215.4532.504.
- 1030
- 1031 Snyder, J. P., 1987. Map Projections-A Working Manual. U. S. Geological Survey
1032 Professional Paper 1395. U. S. Government Printing Office, Washington, DC, 191-202.
- 1033 Trammell, H.J., Li, L., Jiang, X., Smith, M., Hörst, S. and Vasavada, A., 2014. The global
1034 vortex analysis of Jupiter and Saturn based on Cassini Imaging Science Subsystem. *Icarus*
1035 242, 122-129. doi:10.1016/j.icarus.2014.07.019.
- 1036 Trammell, H.J., Li, L., Jiang, X., Pan, Y., Smith, M. A., Bering, E. A., Hörst, S. M.,
1037 Vasavada, A. R., Ingersoll, A. P., Janssen, M. A., West, R. A., Porco, C. C., Li, C., Simon,
1038 A. A., and Baines, K. H., 2016. Vortices in Saturn's Northern Hemisphere (2008–2015)
1039 observed by Cassini ISS. *J. Geophys. Res. Planets* 121, 1814–1826,
1040 doi:10.1002/2016JE005122.
- 1041 Vasavada, A.W., Hörst, S.M., Kennedy, M.R., Ingersoll, A.P., Porco, C.C., Del Genio,
1042 A.D., West, R.A., 2006. Cassini imaging of Saturn: Southern hemisphere winds and
1043 vortices. *Journal of Geophysical Research*, 111, E05004. doi:10.1029/2005JE002563.
- 1044 West, R.A., Baines, K.H., Karkoschka, E., Sánchez-Lavega, A., 2009. Clouds and
1045 aerosols in Saturn's atmosphere. In: Dougherty, M.K., Esposito, L.W., Krimigis, S.M.
1046 (Eds.), *Saturn from Cassini-Huygens*. Springer, Netherlands, pp.161–179.
- 1047
- 1048 Wong, M.H., de Pater, I., Marcus, P.S., Asay-Davis, X., Go, C.Y., 2011. Vertical
1049 structure of Jupiter's Oval BA before and after it reddened: What changed? *Icarus* 215,
1050 211-225. Doi:10.1016/j.icarus.2011.06.032.
- 1051
- 1052 Youssef, A. and Marcus, P. S., 2003. The dynamics of Jovian white ovals from formation
1053 to merger. *Icarus* 162, 74-93. doi: 10.1016/S0019-1035(02)00060-X.