Revised version for Icarus: 2006 April 24

Merging circulations on Jupiter: observed differences between cyclonic and anticyclonic mergers

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Abstract

The dynamics of mergers of large circulations in Jupiter's atmosphere may permit different models of the atmosphere to be tested. We report well-resolved observations of such events at visible wavelengths: three anticyclonic and three cyclonic events. A merger of anticyclonic white ovals in the South South Temperate domain (2002 March) is compared with the previously reported merger of ovals BE and FA in the South Temperate domain (2000 March). In each case, the two similar-sized ovals converged rapidly once they were separated by less than the sum of their diameters; they orbited around each other anticyclonically during the merger; the merged oval initially had the same rapid drift as the western parent; and, in an unexpected similarity, a cyclonic oval emerged westward from the point of merger. Evidence suggests that a merger of smaller ovals in the North North Temperate domain (2002 February) had similar dynamics. In contrast, mergers of cyclonic ovals in the North Equatorial Belt ('barges': 2001 November, 2005 May) proceeded in a different manner. The two parent barges showed no consistent acceleration towards each other as they converged; on contact there was no obvious sign of mutual circulation, and the low-albedo regions had almost passed each other before they finally merged; and the resulting barge had a drift rate intermediate between the two parents, and a length that was greater than either parent. Again, a third such event involving a smaller barge (2002 December) showed many of the same characteristics. These observations define different dynamical behaviour during anticyclonic and cyclonic mergers.

Key words: Jupiter, atmosphere; Atmospheres, dynamics.

1. Introduction

The atmosphere of Jupiter is organized into latitudinal domains, separated by permanent jets, and commonly characterised by long-lived vortices, whose dimensions are a significant fraction of the width of the domains. The existence of long-lived vortices can be accommodated by a wide range of alternative models of the atmosphere (Marcus 1993; Dowling 1995; Vasavada and Showman 2005). However, many key parameters of these models are still not uniquely determined. Using a multidimensional model of the atmosphere with different wind speeds in different layers, it is now possible to considerably constrain the possible atmospheric profiles to reproduce observed patterns of dynamical interactions (Garcia-Melendo et al., 2005; Morales-Juberías et al., 2003; Morales-Juberías and Dowling, 2005). To provide further data to constrain the models more rigorously, it may be useful to study the interactions between vortices.

Anticyclonic vortices include most of the large, long-lived features on the planet, mostly in the form of anticyclonic white ovals (AWOs). Many models and simulations have predicted that anticyclonic vortices should readily merge (Ingersoll and Cuong, 1981; Sommeria et al., 1988; Williams and Wilson, 1988; Marcus, 1988, 1993; Dowling and Ingersoll, 1989). However large AWOs, as observed from Earth, generally do not do so; instead they either repel each other, or adopt a constant spacing which may be stable for years (Rogers 1995; Rogers et al., 2004). Smaller examples, as observed from spacecraft, do frequently merge with each other or with larger ovals (MacLow and Ingersoll, 1986; Morales-Juberias et al., 2002a; Li et al., 2004). However, many or most of these are small vortices travelling rapidly along the jets, which may be of a different type from the larger, long-lived, slow-moving ovals. Therefore it was of great interest when the three largest and longest-lived AWOs, in the South Temperate domain, underwent two successive mergers in 1998 and 2000, leaving only one merged oval (Sanchez-Lavega et al., 1999, 2001; Rogers et al. 2000; Rogers and Mettig, 2001; Rogers et al., 2003).

We now report two other mergers of smaller AWOs in different latitudinal domains on Jupiter, revealed by the recently increased resolution of amateur imaging techniques. For the first time, mergers between long-lived, equal-sized AWOs are resolved at visible wavelengths. There are clear similarities between the dynamics of these events. One special feature, definite in one case and probable in two others, is the appearance of a cyclonic oval from the point of merger with relative westward motion, as predicted in recent models by Youssef and Marcus (2003) and Marcus (2004).

Cyclonic vortices generally can not be tracked for as long as anticyclonic ones. But large long-lived examples do appear in the North Tropical domain, in the form of low-albedo circulations called 'barges' (Rogers 1995; Hatzes et al., 1981). Their interactions have not yet been the subject of detailed modelling. Mergers between them are not uncommon and we report three well-observed examples, which showed nearly identical dynamics, and were clearly different from the mergers of AWOs.

The locations of the six events are shown in Fig.1, and the measured parameters of the merging ovals are listed in Tables 1 and 2.

2. Observations and analysis

All data are from amateur observers imaging at visible wavelengths with telescopes of apertures 200-410 mm, using CCD cameras or webcams, unless otherwise stated. The names of the observers are given in the figure legends. Details of their equipment will be given in our regular reports on each apparition in the *Journal of the British Astronomical Association.*

The number and resolution of good images available have greatly improved in the last few years. In 1999-2002, most images were from CCD cameras, often with resolution increased by summing multiple over-sampled images (Cidadão, 2001; Grafton, 2003). From 2002 onwards, the number and quality of images have further increased through the widespread use of affordable webcams. Their high sensitivity and speed allow hundreds of images to be recorded within about one minute, with very short exposures (Davis and Stamp, 2003). Software, most commonly Registax, is then used to select, align, and sum the images that contain sufficient data at high spatial frequencies, thus overcoming the effects of atmospheric turbulence (Berreroets, 2004). Further processing can then be applied to enhance and sharpen the resulting image.

In particular, images by P.C.S. in 2001-02 were taken from Arkansas with a 31 cm Schmidt-Cassegrain telescope and Olympus C-3000 CCD camera. Images by A.C. in 2002 were taken from Portugal with a 25 cm Schmidt-Cassegrain telescope with adaptive optics, and a ST-5C CCD camera. Images by D.P in 2005 were taken from Barbados with a 23.5 cm Schmidt-Cassegrain telescope (Celestron) and a Lumenera webcam. All images used in this report have been processed by the observers, using various programs.

The other innovation that has improved the quality of amateur Jupiter studies is the digitisation of measurements, using the PC-/WinJUPOS program, <http://jupos.org> (Rogers and Mettig, 2001). All longitudes and latitudes are measured using PC-/WinJUPOS.

Longitudes are given in System III (pre-1997 definition: sidereal rotation period 870.536°/day), unless otherwise stated. 'Fast' and 'slow' refer to rotation periods, thus 'faster drift' denotes more rapidly decreasing longitude while 'slower drift' may denote increasing longitude.

Separations of ovals are quoted in degrees longitude from centre to centre. Latitudes are zenographic. In all images, south is up and longitude increases to the right (western side).

Anticyclonic and cyclonic senses are inferred from the precise latitudes of the ovals, in relation to the Voyager zonal wind profile, as well as from their characteristic appearances. Imaging by Voyager, Galileo, Cassini, and the Hubble Space Telescope (HST) has clearly established the sense of circulation for long-lived AWOs in the latitudes considered here, and for cyclonic white ovals trapped between pairs of AWOs, and for the cyclonic dark 'barges' in the NEB. In the case of shorter-lived white spots that we record during the mergers, cyclonic vorticity is inferred mainly from the latitude, as considered further below.

3. Results

3.1. Merger of AWOs in the South Temperate domain (2000 March: ovals BE and FA)

The three South Temperate AWOs had been familiar features since the early 1940s (Rogers 1995), but two of them apparently merged during solar conjunction in 1998, forming a larger oval named BE (Sanchez-Lavega et al., 1999; Rogers and Mettig, 2001). Oval BE then converged on the third oval, named FA. Their separation fluctuated during 1999, but they eventually merged in 2000 March, as already reported (Rogers et al., 2000, 2003; Sanchez-Lavega et al., 2001). Developments differed in the visible, near-infrared continuum, and methane absorption wavebands, probably representing different currents at different altitudes as the two ovals were caught in a mutual vortex (Rogers et al., 2000; Sanchez-Lavega et al., 2001; Morales-Juberías et al., 2003). Here we summarise the observations at visible wavelengths for comparison with other mergers (Fig.2).

Throughout most of the 1999/2000 apparition, BE and FA were ~15° apart (centre to centre in longitude), separated by a small cyclonic white oval, but this disappeared in mid-Dec. as they were passing the Great Red Spot. (Sanchez-Lavega et al., 2001, presented HST imagery confirming that this spot was cyclonic, and Pic du Midi imagery indicating that its disappearance involved being drawn southward around oval BE.) Within weeks, BE and FA began rapid convergence.

In longitudinal drift, the eastern oval (BE) showed modest oscillations but no rapid change. The western oval (FA) had a more rapid drift, which accelerated by 0.05°/day in early Feb., ~6 weeks before merger. At that time the centres of the ovals were 12° apart, just less than the sum of their diameters (then ~14.7°, previous mean 13.5°); that is, the space between them was about as large as the smaller oval. FA was already slightly further south and moved a further ~0.7° south around this time, as if beginning to orbit BE.

They finally collided and merged during just one week, having been almost in contact on March 15. Oval FA remained distinct up to March 20, but oval BE was invisible or disrupted on March 17-20 (the period when methane-band images revealed its bright cloud cap circulating around BE: Sanchez-Lavega et al., 2001). By March 24 there was just one single irregular white complex. Imaging was severely limited as the planet was nearing solar conjunction, so the details were unclear, but a single AWO emerged.

Cyclonic white spots were noted before and after the merger. The cyclonic oval lying between ovals BE and FA disappeared 3 months before the merger (see above). During the merger, a presumed cyclonic bright spot appeared on the western edge of the merging AWO (black arrowhead in Fig.2a). (It was first seen in an I-band image from the Pic du Midi on March 21: Rogers et al., 2000; Sanchez-Lavega et al., 2001). It was presumed to be cyclonic from its latitude. Although it could conceivably have been a transient anticyclonic vortex, thrown into cyclonic latitudes in this exceptional event, it seems much more likely to have been a cyclonic oval by comparison with the S.S. Temperate event and with modelling (see below). It apparently persisted at least till April 3, ~6° west of the merging AWO, but was not seen thereafter.

By April 7 the merged AWO, named 'BA', lay close to the original track of the eastern oval (BE), but had a more rapid drift.

Several months later, after solar conjunction, oval BA was still visible, large but of low contrast (Rogers et al., 2004). Longitude measurements in 2000 June-Sep. indicated some iregularity in its motion, possibly oscillations, but the limited observations available did not allow any pattern to be established. Later the drift was steady, -0.13°/day. Oval BA marked the east end of a very dark broad sector of the South Temperate Belt, with a small AWO to its west but no cyclonic oval remaining, as confirmed by Cassini images in 2000 Oct.

3.2. Merger of AWOs in the South South Temperate domain (2002 March)

During the Voyager encounters, there were 12 AWOs at 40.5°S, including an impressive array of 9 AWOs spaced 20-30 deg. apart, alternating with cyclonic circulations. It was evident from ground-based observations at the time that this series was unusually prominent, probably created in association with the largescale recirculation and whitening of sectors of the S. Temperate Belt at the time (Rogers, 1995). Since amateur images improved to be able to image these AWOs routinely, in 1986, there have always been 6 or 7 such ovals (see our reports in the *Journal of the British Astronomical Association*, most recently Rogers et al., 2004, and manuscripts in preparation). Although it is not always possible to be certain whether an oval has persisted though solar conjunction with variable drift rate, our best estimate is that from 1986 to 2001, four new ones appeared and five disappeared. Some disappeared by shrinking to invisibility, and some by possible mergers, though never at a time when they could be observed. These included a pair at the west end of a chain, which probably merged in 1992 March (Rogers and Foulkes, 1994) to form the oval A7. While some of these AWOs lasted only 1-2 years, most of them have lasted much longer with an estimated mean lifetime of 20-25 years (our unpublished data). Whether they are always separated by cyclonic circulations is difficult to establish with certainty because only some cyclonic circulations are visible as white ovals; others have very low contrast at ground-based resolution. However the improved resolution of recent years is consistent with cyclonic circulations separating most if not all of the closely spaced AWOs.

Although the AWOs initially had irregular spacings of 30-60°, they tended to drift closer. In 2001/02 the last four (named A4 to A7, most of them tracked since the 1980s) had separations of only 10-20°, sometimes converging and rebounding on a timescale of months. In 2002 March, the most westerly pair of them converged rapidly and merged (Fig.3). This happened while these AWOs were overtaking oval BA, which in turn was overtaking the GRS. This is the first time such a merger has been directly observed, and it was remarkably similar in detail to the merger of larger AWOs in the S. Temperate domain two years earlier. A preliminary account of these results have been presented (Rogers et al., 2002).

Before their final convergence, the eastern oval (A6) had an oscillating drift in longitude, until it markedly decelerated in March. The western oval (A7) had a more rapid drift, gradually accelerating.

Final convergence began when the eastern oval (A6) decelerated by 0.22°/day around March 10-14, 12 d before the merger started. At this time the centres of the ovals were 9° apart, slightly more than the sum of their diameters (~7.2°). Oval A6 was already slightly further north and moved a further ~0.5° north at this time, as if starting to orbit the other AWO.

The final events of merger were very rapid, lasting only a week. The two ovals orbited round each other anticlockwise through 180° within less than 4 days (March 21-24). They appeared to be merging but lobed on March 25, then unresolvable on March 26, but double and rotating again on March 28, implying that they had orbited through more than 360° (or alternatively, that a single merged oval was pulsating). From March 30 onwards, there was only a single merged AWO. At this time it was close to the original track of the eastern oval, but retained the rapid drift of the western oval.

Cyclonic white spots were conspicuous before and after the merger. Before the merger, a cyclonic white oval (labelled C1 in Fig.3) lay between the converging AWOs. It brightened on March 21 as the AWOs began to interact, then was not resolvable from the merging AWOs for 3 days. On March 25 a cyclonic bright spot (labelled C2) appeared on the west edge of the merging AWO, and persisted with a slow drift for at least 5 weeks. It could have been the same as C1. It was presumed to be cyclonic from its latitude (39 deg.S, the same that we measure for normal cyclonic white spots in this domain), and its longevity makes it implausible that it could have had a contrary circulation.

Near-infrared images in the I-band (~800-1000 nm) were taken on many dates in addition to visible light images, and they generally showed similar appearances, except once on March 21 (Fig.3a). This image could indicate that the deep cores were converging without large-scale orbiting, as was shown for the BE-FA merger (Sanchez-Lavega et al., 2001; Morales-Juberías et al., 2003), but the observation was unconfirmed.

A second merger probably occurred during solar conjunction: In 2002 Oct., only five S.S. Temperate AWOs were present, suggesting that the merged oval A6/7 had merged with A5 in turn (Fig.3c). This row of five AWOs has remained stable up to 2006. Meanwhile two new long-lived AWOs arose in early 2004 at other longitudes, restoring the total of seven AWOs spread around this latitude band.

3.3 Merger of AWOs in North North Temperate domain (2002 February)

These AWOs were smaller than those described above, and their merger (Fig.4) was recorded due to the intense coverage of these longitudes prior to the S.S. Temperate event, which was visible in the same series of images.

The eastern AWO (no.1) was a well-defined bright oval with a dark rim. It had appeared in 2000 Sep, and it decelerated 1 month before merger. The western AWO (no.2) was a small rimless white spot only observed for a few months.

The final convergence began in early Feb. when AWO-2 accelerated by 0.4°/d, 1-2 weeks before the merger. At this time the ovals were 12° apart, still much more than the sum of their diameters.

The merger was not followed in detail because both ovals virtually disappeared, but the chart implies that they merged in late Feb. The image on Feb.15 appears to show them about to merge, with AWO-2 swapping places with the dark spot (no.3, probably cyclonic) which had been between them. The result was a single AWO (from Feb.22 onwards).

In the adjacent cyclonic belt, a dark spot was dynamically involved in the merger, and a bright spot may have been created in it. The dark spot (no.3) was initially part of the dark rim of

AWO-1, but later it detached as a separate retrograding dark spot; such spots can be cyclonic circulations (Rogers, 1995; Morales-Juberías et al., 2002b). It passed AWO-2 during the merger, then persisted with increasing retrograde drift. A tiny bright spot on its S edge on Feb.25 and 27 (labeled 3* in Fig.4a) was probably a short-lived cyclonic eddy created in the merger.

The merged AWO resembled AWO-1 in appearance, with its dark rim, and was close to its original track, but with a more rapid drift rate. It still existed in the first half of 2003, having decelerated again.

3.4. Merger of cyclonic barges in the North Equatorial Belt (2001 November)

Sets of dark brown cyclonic circulations called 'barges', interspersed with AWOs, are common in the North Tropical domain, typically about a year after the low-albedo North Equatorial Belt has broadened northwards (a NEB expansion event: Rogers 1995). This was the case in 1997 and 2001 and 2005. Whereas AWOs in a given latitudinal domain all have approximately the same low ellipticity, barges vary much more in length (in longitude) than in width (in latitude). Historically they last for 1-2 years, although in 2001 the set of barges had existed for longer. In particular barges B1, B2, and B3 had existed since 1997, as had an exceptionally bright and fast-moving AWO at 19°N called white spot Z (WSZ) (Rogers et al, 2004).

WSZ has always shown more rapid longitudinal drift than other features in the domain. Thus it appears to a manifestation of a persistent wave, whose physical basis has not been investigated. West of it, new barges emerge; east of it, as it approaches other spots, they are either destroyed or accelerated. This has never yet led to an observed merger of AWOs, but in three cases reported here, it has led to mergers between cyclonic barges.

Barges B2 and B3 had appeared in 1997, initially close together with an AWO between them. They then drifted apart and the AWO disappeared, although at least one small anticyclonic vortex remained oscillating between them in the form of a small dark spot (Rogers et al, 2004). After the NEB expansion event in 2000, this spot became invisible in the low-albedo belt in early 2001, and there was no evidence of any coherent anticyclonic feature between the barges, which were 40-45° apart. It was probably the approach of WSZ which impelled barge B3 to have a rapid drift that caused it to converge with barge B2; concordantly, it was ~0.8° further south than most barges (Table 2 and Fig.5c). This led to the merger of barges B2 and B3 (Fig.5). A preliminary account has been given (Rogers, 2002).

Their drift rates and latitudes showed little change over >2 months before the merger, apart from typical fluctuations. There was no final acceleration.

When the barges came into contact, there was no sign of circulation. In fact, although the two barges formed a single complex by Nov.12, they apparently retained their identities and drifts, sliding past each other over the following nine days: B3 slid past B2 and partly emerged southeast of it, then becoming indistinct (arrow in Fig.5a). However a merger does seem to have occurred as indicated by the properties of the single barge that emerged.

The resulting barge (B2/3) was initially longer than either parent. It had a drift rate intermediate between those of the two parents, but was gradually decelerating. It had a latitude intermediate between those of the two parents, but was gradually drifting north. It remained a prominent stable barge for the next 4 months, despite close interactions with bright turbulent convective streaks in the cyclonic NEB. But then its deceleration brought it within 10° of WSZ, which propelled it to higher drift rate and lower latitude as had happened to barge B3 the previous year.

3.5. Merger of cyclonic barges in the North Equatorial Belt (2002 Dec.)

Barge B2/3, resulting from the merger in 2001, continued to travel ~20° ahead of WSZ, with fluctuations, until 2002 Dec., when it approached a larger long-lived barge, B1 (Fig.6). This event is less reliable as an example of barge merger, for two reasons. First, the NEB expansion event had ended, so the north edge of the visibly dark NEB was at the same latitude as the barges, and this strong albedo boundary may have affected both the real morphology of the barges, and their appearance in the sharpened images. Secondly, by this time, B2/3 was merely a small indistinct dark patch on the NEB north edge and would not have been identified as a barge apart from its history; it was much smaller than B1. B1 was a large dark barge, with a northward cusp and an anticyclonic ring northeast of it, which indicated that it was distorting the surrounding currents in a manner typical of these cyclonic barges (Rogers et al., 2004).

B1 and B2/3 both changed speed one month before merger, thus converging rapidly: the convergence speed and difference in latitude were both greater than in 2001. But on contact, the two barges merged in a way similar to 2001.

They contacted on about Dec.22. On Dec.30, the combined shape suggested that B2/3 had proceeded past B1 to its southeast corner, as in 2001. This shape then persisted until Jan.13. Then from Jan.18 onwards there was a single prominent barge, longer than B1 before the merger, and with intermediate drift rate and latitude.

3.6. Merger of cyclonic barges in the North Equatorial Belt (2005 May)

These two barges, here called B1 (eastern) and B2 (western), behaved almost identically to the pair in 2001 (Fig.7). These were not the same barges as the previous set: B1 had appeared along with other new barges in late 2004 after a new NEB broadening event. B2 had appeared in early 2004, and had apparently been accelerated indirectly by WSZ. B2 was the easternmost (preceding) member of a rapidly moving group, being followed by a new AWO, then by another new barge, and finally by WSZ, whose rapid longitudinal drift was now shared by the entire group.

As in the approach in 2001, B2 was about 0.8° further south than B1. The parameters did not change significantly for several months, until mid-April. Then, 2-3 weeks before the merger, B2 drifted even faster, while B1 began moving further north (reaching a maximum latitude 16.5°N on May 4 as they came into contact). However these changes may have been incidental: such changes had not occurred prior to the previous mergers of barges, and they may have been induced by a substantial bright convective streak ('rift') in the cyclonic NEB, which passed the barges in mid-April.

When the barges came into contact, there was no visible circulation. After contact, they became indistinct (only a diffuse reddish cloud was visible for several days) but this resolved to show that B2 had slid past B1 and partly emerged southeast of it without change of latitude, although the relative albedo of the two components varied rapidly. However a merger clearly occurred as indicated by the properties of the single barge that emerged.

The resulting barge survived despite an encounter with another vigorous 'rift' in the NEB in mid-May, and in June, it again became a distinct barge as dark as the others and twice as long as either parent, with a drift rate intermediate between those of the two parents.

4. Discussion and Conclusions

4.1. Anticyclonic mergers

Previous observations of anticyclonic ovals merging have mostly been made using spacecraft images (MacLow and Ingersoll, 1986; Morales-Juberias et al., 2002a; Li et al., 2004). They pertain mostly to small vortices, especially the special type which move rapidly at the full speeds of the jets, merging either with each other or with larger vortices. Long-lived, medium-to-large-sized ovals drift much more slowly in longitude relative to the mean wind speed for their latitude, being only weakly entrained by the local zonal flow (Rogers, 1995; Morales-Juberias et al., 2002a,b). Mergers of equal pairs of such ovals are very rare (Rogers 1995). In fact, the merger of ovals BE and FA was the first such event to be observed as it happened, and even that was recorded under difficult conditions. Thus the present observations of the S.S. Temperate AWOs are the most detailed ever obtained of such an interaction at visible wavelengths.

The common features of the S. Temperate and S. S. Temperate mergers of AWOs were as follows (Fig.8a). (Some of these features were also shown by the minor example in the N.N. Temperate region, as noted above.)

1. The western oval had more rapid drift (a precondition for any convergence), and was also slightly further south.

2. Convergence may have been triggered by the ovals' drifting past a larger AWO in the adjacent domain (the GRS for the S. Temperate ovals, oval BA for the S.S. Temperate ovals); passage past the GRS commonly destabilises circulations in the S. Temperate domain [Rogers, 1995]. In both cases, final convergence began when the ovals were separated by approximately the sum of their diameters. In view of the substantial drift change and the coordinated latitude change, this was probably the first sign of mutual attraction of the vortices. Even so, in the last 12 days before merger began for the S.S.Temperate AWOs, the ratio of difference in speed (0.36°/d) and latitude (~0.6°) was only half that expected from the mean zonal wind gradient in these latitudes as observed from spacecraft (Limaye, 1986; Garcia-Melendo and Sanchez-Lavega, 2001; Porco et al., 2003). In the last month before merger began for the S. Temperate AWOs, the ratio of difference in speed (0.07°/d) and latitude (~0.9°) was very much less than expected from the mean zonal wind gradient (Sanchez-Lavega et al., 2001). The ovals were still moving as large stable structures, not fully entrained by the local winds.

3. When the ovals were virtually in contact, rapid changes occurred leading to merger within only a week. Anticyclonic orbiting was observed directly for the S.S. Temperate example, and may also have occurred in the S. Temperate example for which it was recorded in methane band images (Sanchez-Lavega et al., 2001). The process has been successfully simulated by Morales-Juberias et al. (2003).

4. The merged oval, within days, returned close to the extrapolated longitude track of the eastern oval, but initially had the rapid drift of the western oval. It was only slightly larger than its parents.

5. A cyclonic white spot appeared from the point of merger, lying on the west side of the merging AWO.

Early models of vortices in the jovian atmosphere predicted that they should readily converge and merge (see references in Introduction). Recently, by modelling the vortices as a Karman vortex street which is trapped within a Rossby wave, it has been shown that rows of AWOs can remain stable as observed (Youssef and Marcus, 2003). This model has also shown how neighbouring AWOs can eventually merge (Youssef and Marcus, 2003; Marcus, 2004). A crucial role is played by the cyclonic ovals which are hypothesised to always separate the AWOs. Their simulation showed that a cyclonic oval between two AWOs should move north and west around the western AWO when it merges with the eastern AWO.

The present observations provide strong support for this prediction. In the BE-FA merger, we had already noted the appearance of a cyclonic white spot in the appropriate location, although conditions could not allow it to be clearly resolved nor tracked. In the S.S. Temperate AWOs merger, we clearly observed a cyclonic white oval appearing and retrograding as predicted, and it may indeed be the same one which previously separated the two AWOs. In the N.N. Temperate AWOs merger, a dark patch performed the same maneuver, and was briefly associated with a small white spot which may indicate that a cyclonic oval did indeed move as predicted.

In each case the cyclonic spot did not remain associated with the merged AWO, probably because there were no more large AWOs west of it to trap the cyclonic oval.

4.2. Cyclonic mergers

These are probably much more frequent, and yet not frequently observed. This is because cyclonic circulations are generally less well defined and apparently less stable (MacLow and Ingersoll, 1986; Morales-Juberias et al., 2002b). So only the NEB barges, in the North Tropical domain, are commonly distinct enough for mergers to be observable from Earth.

In the NEB, as in other domains, cyclonic barges commonly form alternating chains with AWOs, although the spacing is variable and isolated examples also occur. They sometimes converge, either through random motions or through the influence of rapidly-moving WSZ. This has never yet led to an observed merger of AWOs, perhaps because they dissipate before merger. Likewise, in the one recorded instance of a probable merger of AWOs in this latitude, in 1968, involving a similar fast-moving AWO, the interaction itself was not observed (Reese and Solberg, 1969). In contrast to the rarity of anticyclonic mergers, several examples of probable mergers between cyclonic barges have been noted in the historical record (Rogers, 1995). There is no evidence that barges repel each other, and it is possible that close pairs tend to merge if not separated by an AWO. In the last six years of intense observations (our data in preparation), pairs of barges have never converged closer than 20° without either developing an AWO between them, or dissipating, or – in the three instances reported here – merging.

The common features of the three NEB barge mergers were as follows (Fig.8b).

1. In longitudinal drift, the western barge was moving much faster because it was immediately east of the long-lived, fast-moving AWO called white spot Z (2001, 2002), or east of a second AWO just east of white spot Z (2005). It was also about 0.8° further south than the eastern barge. The

implied speed gradient is 0.5°/d per degree latitude (2001, 2002, 2005), which is much less than the mean zonal wind gradient of 1.2°/d per degree latitude over the same latitude range (Limaye, 1986; Garcia-Melendo and Sanchez-Lavega, 2001; Porco et al., 2003; and our unpublished data for 2003/04). This again illustrates the well documented fact that large circulations on Jupiter are only weakly entrained by the local zonal winds.

2. The drift rates and latitudes showed no consistent change for ~2 months before the merger, suggesting that there was no mutual interaction until they were in contact. This was clearly the case in 2001. Mutual acceleration did occur 2-4 weeks prior to the 2002/03 and 2005 mergers, which involved smaller barges, although they were still ~18-23° apart at the time. This could merely be due to external influences and random fluctuations typical of such small spots. Alternatively, it could be evidence of a medium-range attraction between these cyclonic circulations (in contrast to the medium-range repulsion, but short-range attraction, observed for anticyclonic circulations).

3. When the barges came into contact, there was no obvious circulation. In each case the western barge appeared to partially overtake the eastern barge, then becoming indistinct, although the albedo patterns may not have revealed immediate changes in circulation patterns (discussed further below). However a merger does seem to have occurred as indicated by the properties of the stable barge that emerged.

4. This merged barge was distinguished by a drift rate intermediate between those of the two parents, by a latitude reverting to that of the eastern parent, and by a length greater than that of either parent. No new spots were created by the merger.

Detailed modelling of cyclonic barge mergers on Jupiter will be necessary to determine whether these observations are consistent with existing models of the atmosphere. The most surprising aspect is that the two barges appear to slide alongside each other on their original tracks before fully merging. It is implausible that they could retain two separate cyclonic circulations while thus tightly in contact. One possibility is that they have small core circulations which initially could slide past each other, prior to merging, while a more extended visible structure (believed to be a thinning in the clouds) persists and proceeds for some distance with the zonal flow in which the barges are embedded. This would be analogous to the structure of large AWOs (Morales-Juberias et al., 2003) but unlikely for cyclonic features without high-level cloud canopies. A more likely possibility is that the circulations do indeed merge on first contact but the periphery remains flexible, still partly entrained by the local zonal winds, for some time, as sketched in Fig.8b. This would be more consistent with the structure of a barge observed in detail by Voyager (Hatzes et al., 1981): it had the strongest winds around the periphery, and the periphery oscillated maintaining constant area. Similar flexible boundaries are also shown by other cyclonic circulations on the planet, unlike the strictly oval structures of anticyclonic circulations.

It remains to be seen whether theories or simulations of cyclonic barges will reproduce this dynamics of merger, which is so different from that of anticyclonic ovals.

Acknowledgements

We are very grateful to all the other observers from the worldwide amateur network who contributed images to this analysis, in particular Tomio Akutsu, Paulo Coelho, Christopher Go, Ed Grafton, T. Ikemura, David M. Moore, Eric Ng, Timothy Parker, Donald C. Parker, Isao Miyazaki, Zac Pujic, Jesus R. Sanchez , P.Clay Sherrod, Kenneth Schmidt, and Tan Wei Leong. The PC-/WinJUPOS program was created by Grischa Hahn and H-J.M., and measurements were also done by G. Adamoli , M. Jacquesson, A. Nikolai, D. Peach and M. Vedovato. We also thank Drs. J. Lecacheux and F. Colas for permission to use an image from the Pic du Midi.

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Table 1
Parameters of merging anticyclonic white ovals

Date, Domain	2000 March	S. Temperate			2002 March	S.S. Temperate			2002 Feb.	N.N. Temperate	
	Names, Dates	Length (deg.)	DL3 (deg/day)	Lat. (deg.S)	Names, Dates	Length (approx.)	DL3 (deg/day)	Lat. (deg.S)	Names, Dates	DL3 (deg/day)	Lat. (deg.N)
Before convergence	Dates (a)				(Aug-Jan.)				(Jan.)		
E. oval	BE	7.9	-0.17	-32.3	A6		-0.74	-40.7	AWO-1	(+0.33)	40.9
W. oval	FA	5.3	-0.18	-33.0	A7		-0.75	-40.8	AWO-2	+0.20	40.5
Final convergence	(Feb.15--Mar.15)				(Mar.10-21)				(Feb.)		
E. oval	BE	8.5	-0.16	-32.8	A6	(3.6)	-0.52	-40.2	AWO-1	+0.54	
W. oval	FA	5.3	-0.23	-33.7	A7	(3.6)	-0.88	-40.8	AWO-2	(-0.20)	
After merger:	Dates (b)				(Mar-Apr.)				(Feb-Apr.)		
AWO	BA	8.3	(-0.26)	-32.5	A6/7	(4.0)	-0.88	-41.0	AWO-1/2	+0.13	40.8
Cyclonic	Cyc.WO	nd	(-0.26)	-30.8	Cyc.WO		-0.37	-39.0	Cyc.(c)	(DS) +0.57	(WS) 37.3
Domain mean			-0.20				-0.68			+0.34	

(a) Length and drift up to 2000 Jan.; lat. to 1999 Nov.
(b) Drift and lat., 2000 Mar.27-Apr.3; size, 2000 Oct.
(c) For cyclonic spot: Drift is for dark spot, latitude for white spot (n=1).

Notes:
Lengths are in degrees of longitude.
Drifts (DL3) are in degrees per day in System 3 longitude (positive westward).
Latitudes are in degrees, zenographic.
Values are typically accurate to approx. +/- 0.6 deg. for lengths,
+/-0.01-0.02 deg/day for drifts (+/- 0.1 deg/day for values in brackets),
and +/- 0.1-0.2 deg. for latitudes (standard error of mean).

Table 2
Parameters of merging cyclonic barges in the North Equatorial Belt

Date	2001 Nov.				2002/03				2005 May			
	Names, Dates	Length (deg.)	DL3 (deg/day)	Lat.	Names, Dates	Length (deg.)	DL3 (deg/day)	Lat.	Names, Dates	Length (deg.)	DL3 (deg/day)	Lat.
Before merger:	(Aug-Nov.) (a)				(Dec.)				(Mar-Apr.)(b)			
P.barge	B2	6.4	+0.2	15.3; 14.9	B1	6.5	+0.32	16.1	B1	(3.1)	+0.17; +0.27	15.7
F. barge	B3	6.4	-0.23	14.3; 14.2	B2/3	~4.5	-0.38	14.6	B2	(3.1)	-0.16; -0.28	14.8
After merger:												
Barge	(Nov-Dec.)	7.7	-0.12	14.8	(Jan.)	7.1	-0.05	15.8	(May)	6.2	0.00	15.3
Barge	(2002 Feb.)	6.6	+0.09	15.6	(Feb-Apr.)	7.1	(~0.00)	15.6	(June-July)	nd	+0.17	15.6
Domain mean			+0.06								+0.13	

(a) Latitude: Sep-Oct. ; Nov.
(b) Drifts changed during April; latitude of B1 also increased in late April.

Notes:
Lengths are in degrees of longitude.
Drifts (DL3) are in degrees per day in System 3 longitude (positive westward).
Latitudes are in degrees, zenographic.
Values are typically accurate to approx. +/- 0.6 deg. for lengths,
+/-0.01-0.02 deg/day for drifts (+/- 0.1 deg/day for values in brackets),
and +/- 0.1-0.2 deg. for latitudes (standard error of mean).

Fig.1 *(This figure will be printed in colour.)*

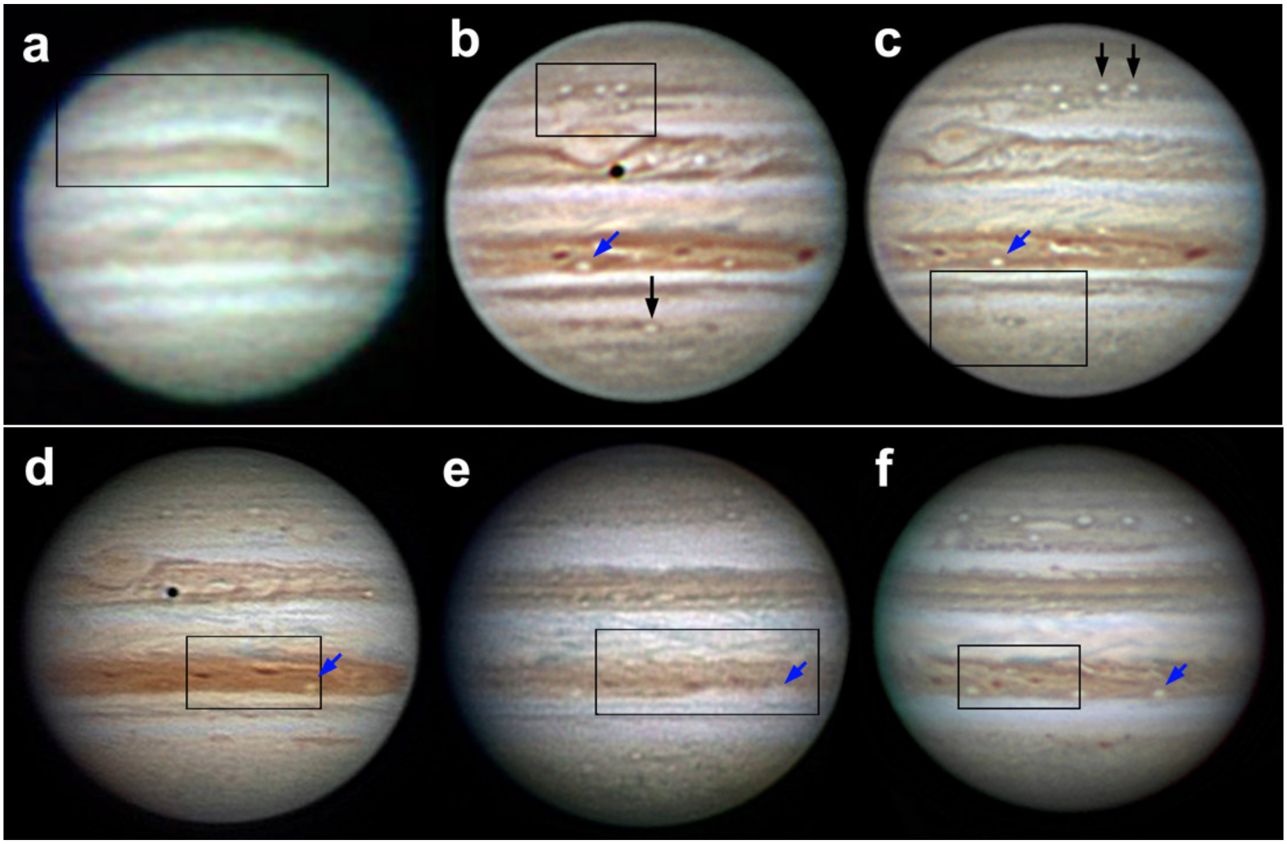


Fig. 1. Images showing the global context of the six mergers reported here.

Each image is one of the earliest in the series and the box outlines the area shown in a subsequent figure. Oblique blue arrows indicate White Spot Z. South is up in all figures in this paper.

(a) 2000 March 17, 01:47 UT (D. Moore, Arizona): Convergence of AWOs in S. Temperate region. (The low quality of this image is due to the low altitude of the planet as the apparition was ending.)

(b) 2002 March 14, 19:57 UT (A. Cidadão, Portugal): Convergence of AWOs in S.S. Temperate region. (Vertical arrow indicates the recently-merged AWO in N.N. Temperate region, shown in (c).)

(c) 2002 Jan.25, 00:57 UT (A. Cidadão, Portugal): Convergence of AWOs in N.N. Temperate region. (Vertical arrows indicate the converging AWOs in S.S. Temperate region, shown in (b).)

(d) 2001 Oct.2, 10:58 UT (E. Grafton, Texas): Convergence of barges in NEB.

(e) 2002 Dec.10, 04:20 UT (D. Peach, England): Convergence of barges in NEB.

(f) 2005 April 20, 01:01 UT (D. Peach, Barbados): Convergence of barges in NEB.

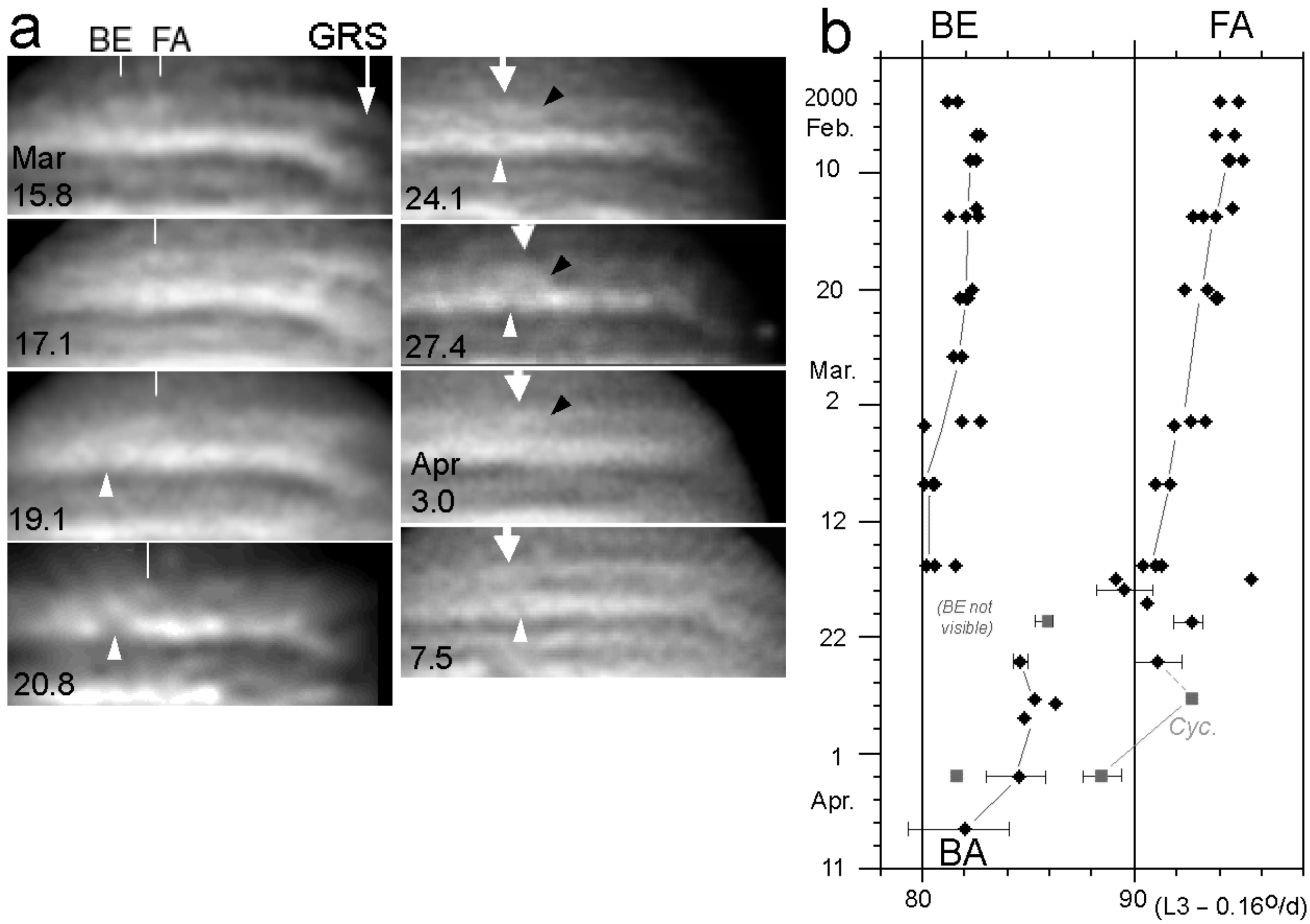


Fig. 2. Approach and merger of S. Temperate ovals BE and FA in 2000.

(a) Images. The two ovals had recently passed the GRS; for earlier images see the BAA report [Rogers et al., 2003]. Vertical white lines indicate oval BE (left) and FA (right). BE was not visible after March 15. White arrow from March 24 onwards indicates the merged AWO. White arrowhead below indicates a dark patch in the S. Tropical Zone at the location of a slow-moving anticyclonic dark ring which formed by merger of retrograding spots 7 months earlier; this vortex may have played a part in the BE-FA interaction as it darkened concurrently. Black arrowhead indicates the new cyclonic white oval.

Images are labelled by decimal date (UT) and were taken by the following observers: 2000 March 15.8, A. Cidadão; March 17.1, D. Moore; March 19.1, T. Parker; March 20.8, A. Cidadão; March 24.1, D. Moore; March 27.4, T.Ikemura; April 3.0, D. Parker; April 7.5, Pic du Midi, by kind permission of Drs. J. Lecacheux and F. Colas.

(b) Longitude chart. The longitude scale moves at –0.16°/d relative to System III. Diamonds, white ovals at latitudes –34.6 to –32.0° (anticyclonic); squares, –31.5 to –29.6° (cyclonic). Before merger, each observation is plotted. During merger, a single mean and range of measured longitudes is plotted for each rotation.

Fig.3

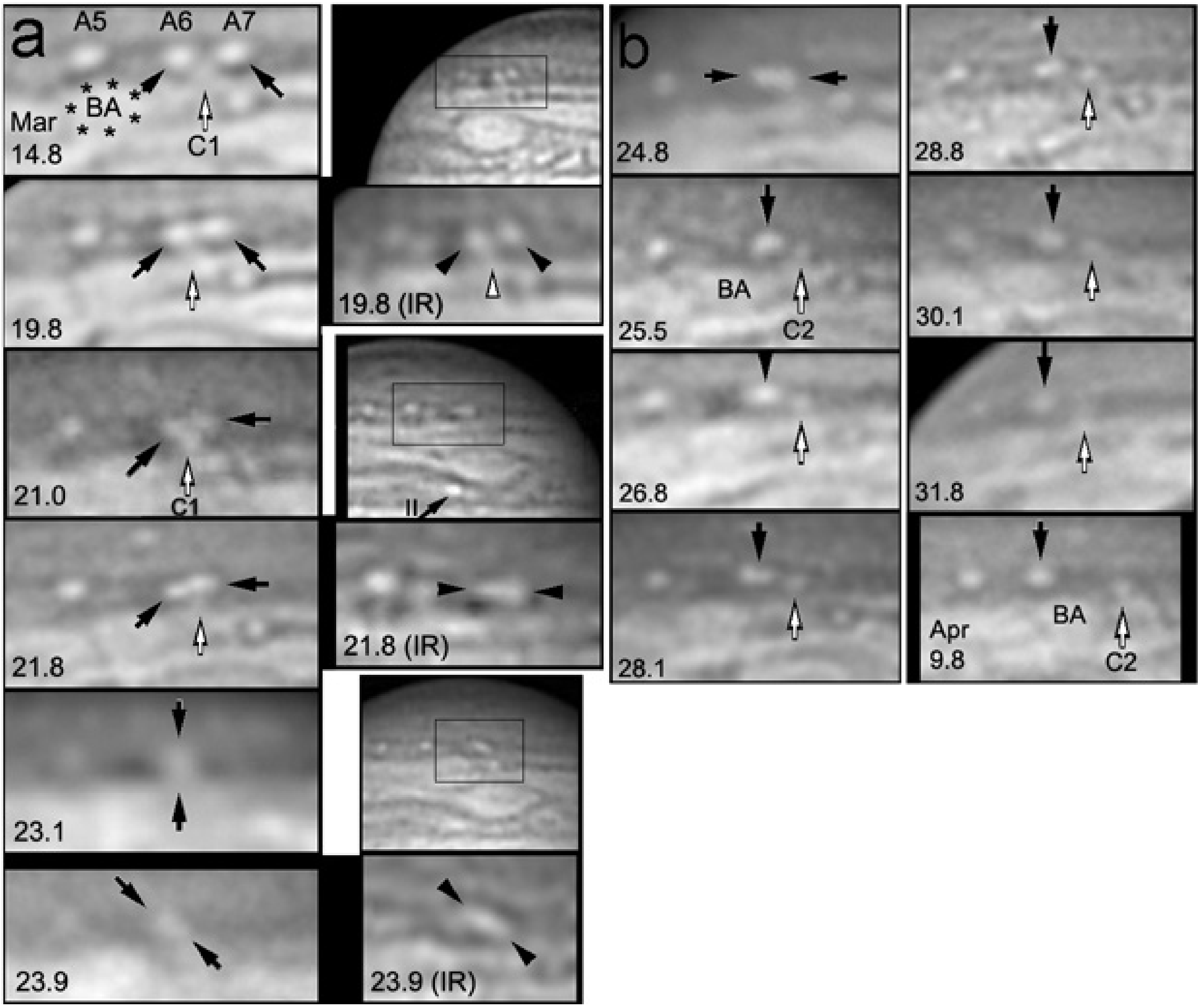


Fig.3. Approach and merger of ovals A6 and A7 in the S.S. Temperate domain.

(a) Images, 2002 March 14-23. Left column, visible waveband; right column, I-band (with context images). The merger happened during a series of interactions between anticyclonic ovals in adjacent domains, as oval BA was overtaking the GRS, and the S.S Temperate ovals were in turn overtaking oval BA. The I-band image on March 21.8 is the only one to show a possible difference from the visible alignment of the merging AWOs. (On the context image, the indicated bright spot is Europa, beside the GRS.) Images were taken by the following observers: 2002 March 14.8, 19.8, 21.0, A. Cidadão; March 21.8, A. Cidadão (similar by P. Coelho), with I-band image by D. Peach; March 23.1, P.C. Sherrod (in bad seeing); March 23.9, P. Coelho, with I-band image by D. Peach.

(b) Images, 2002 March 24-April 9. A vertical dark arrow indicates the merging AWO. The March 28 images may show the original two ovals having rotated through 360° (as indicated) or more, or they may show one merging oval pulsating, and the emerging cyclonic oval C2 may be part of the complex. A white arrow indicates cyclonic oval C2, which may be the same as C1. Images were taken by the following observers: 2002 March 24.8, D. Peach; March 25.5, Tan Wei Leong; March 26.8, A. Cidadão (similar by P. Coelho); March 28.1, E. Grafton; March 28.8, A. Cidadão (similar by D. Peach); March 30.1, D.C. Parker; March 31.8 and April 9.8, A. Cidadão.

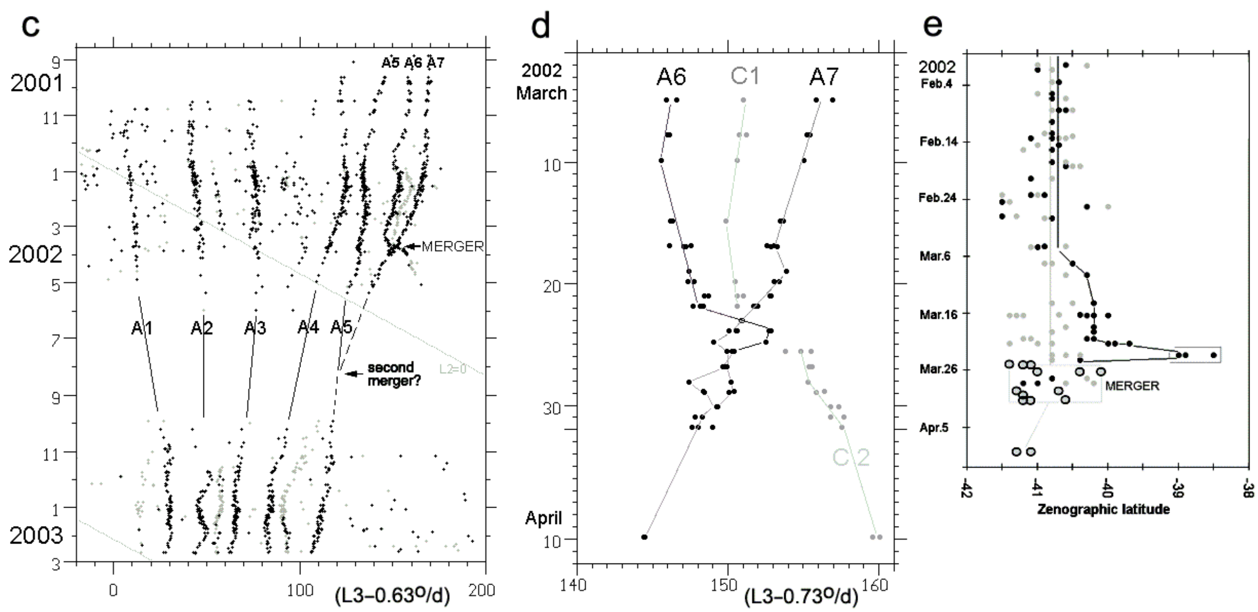


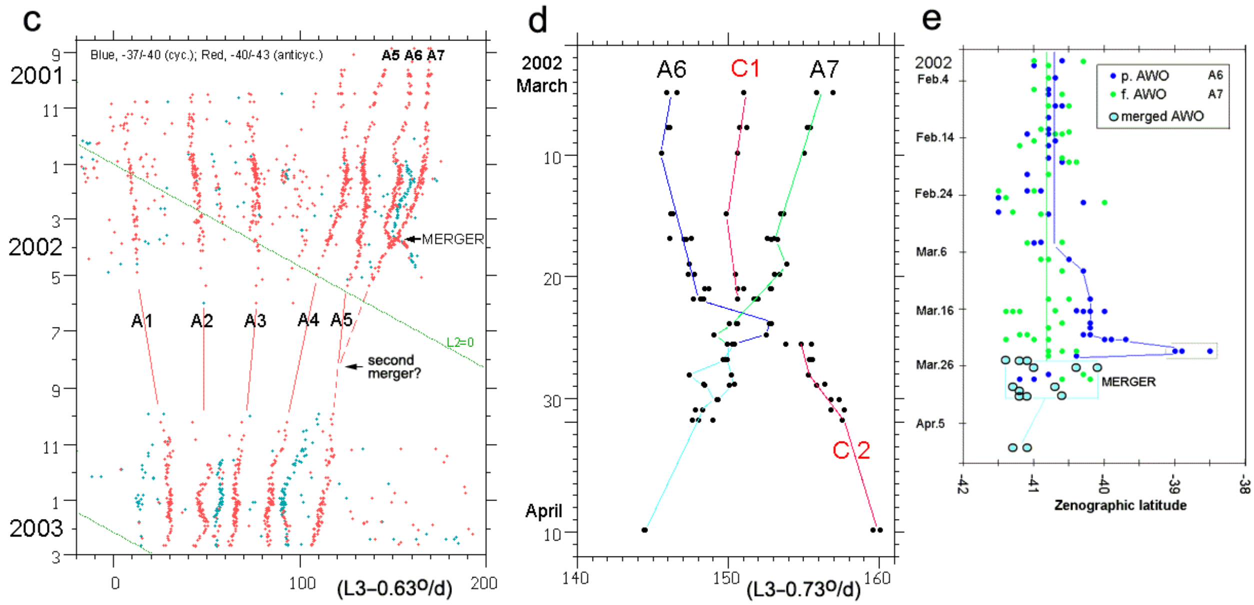
Fig.3 (cont.):

(c) Longitude chart of S.S. Temperate white ovals. Time scale is in months; longitude scale moves at –0.63°/d relative to System III. Black, latitudes –43 to –40° (anticyclonic); gray, –40 to –37° (cyclonic).

(d) Longitude chart showing the merger in detail. Time scale is in days; longitude scale moves at –0.73°/d relative to System III. Black, anticyclonic; gray, cyclonic. Lines are drawn to indicate the minimum number of 'orbits' although the identities of the components were not certain after March 25.

(e) Latitude chart of the merging AWOs. Black, A6 (east); gray, A7 (west). The low latitudes on March 23 may represent the orbiting AWO A6 and/or the emerging cyclonic oval C2, which were not resolved. Larger symbols thereafter represent the merging AWO.

[Alternative colour version for Fig.3c,d,e:]



(c) Longitude chart of S.S. Temperate white ovals. Time scale is in months; longitude scale moves at –0.63°/d relative to System III. Red, latitudes –43 to –40° (anticyclonic); blue, –40 to –37° (cyclonic).

(d) Longitude chart showing the merger in detail. Time scale is in days; longitude scale moves at –0.73°/d relative to System III. Blue and green, anticyclonic ovals; red, cyclonic ovals. Lines are drawn to indicate the minimum number of 'orbits' although the identities of the components were not certain after March 25.

(e) Latitude chart of the merging AWOs. Blue, A6 (east); green, A7 (west). The low latitudes on March 23 may represent the orbiting AWO A6 and/or the emerging cyclonic oval C2, which were not resolved. Light blue symbols thereafter represent the merging AWO.

Fig.4

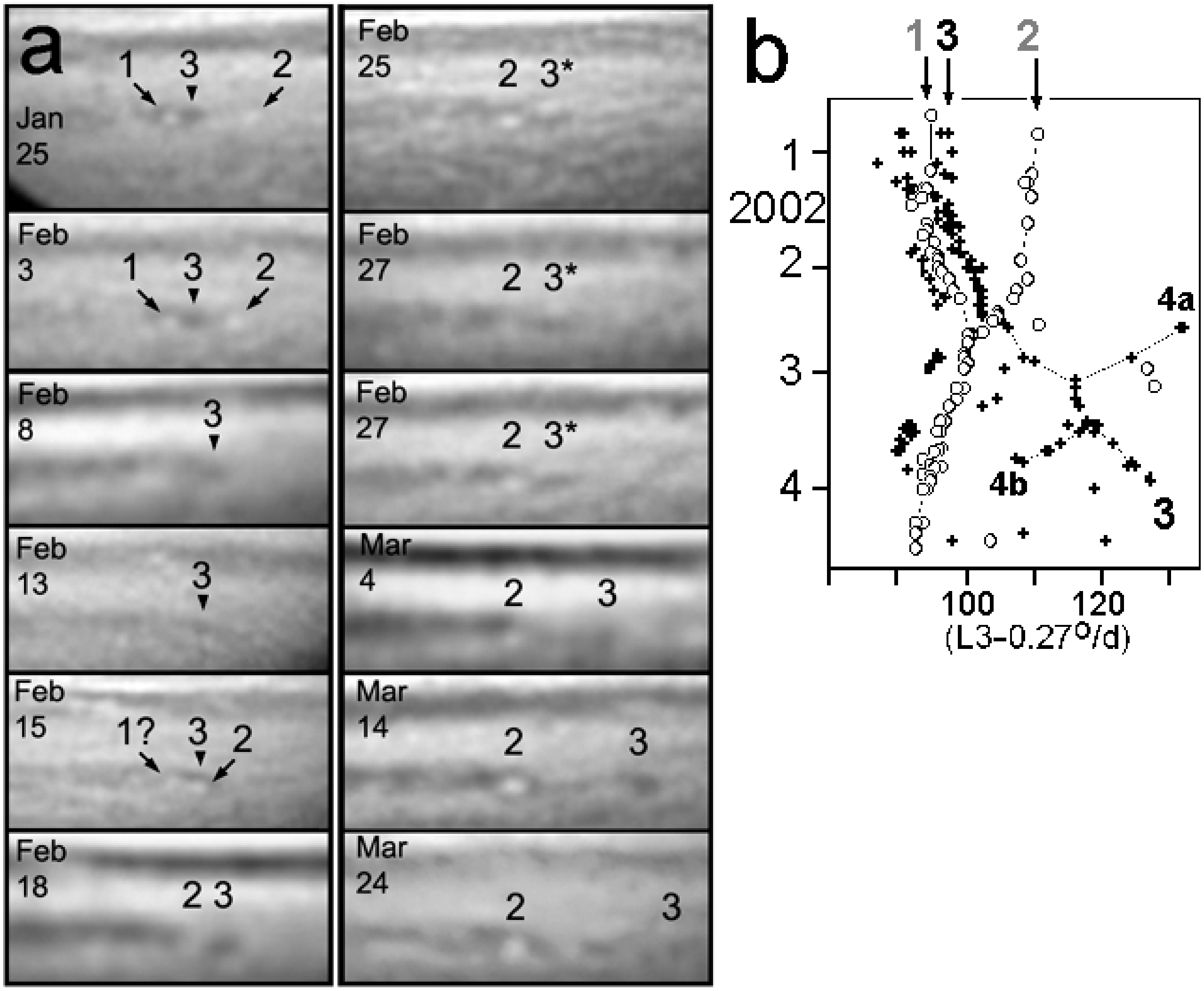


Fig. 4. Approach and merger of AWOs in the N.N. Temperate domain.

(a) Images. Numbers indicate AWOs 1 and 2, and dark spot 3. The merged AWO is labelled 2; dark spot 3 with a small cyclonic white spot on its south edge is labelled 3*. Images were taken by the following observers: 2002 Jan.25.0 and Feb.3.9, A. Cidadão; Feb.8.1, P.C. Sherrod; Feb.13.1, K. Schmidt; Feb.15.1, E. Grafton; Feb.18.0, P.C. Sherrod; Feb.25.0, E. Grafton; Feb.27.5, E. Ng; Feb.29.9, A. Cidadão; Mar.4.1, P.C. Sherrod; Mar.14.8, A. Cidadão; Mar.24.8, D. Peach. **(b) Longitude chart.** Time scale is in months; longitude scale is System 2 (moving at –0.27°/d relative to System III); latitude is +39 to +42°. Open circles, AWOs; black crosses, dark spots. Images confirmed the continuity of dark spot 3 as it swapped places with AWO-2 and subsequently underwent an unrelated interaction with a smaller, rapidly prograding dark spot (labelled 4a; re-emerged as 4b).

Fig.5

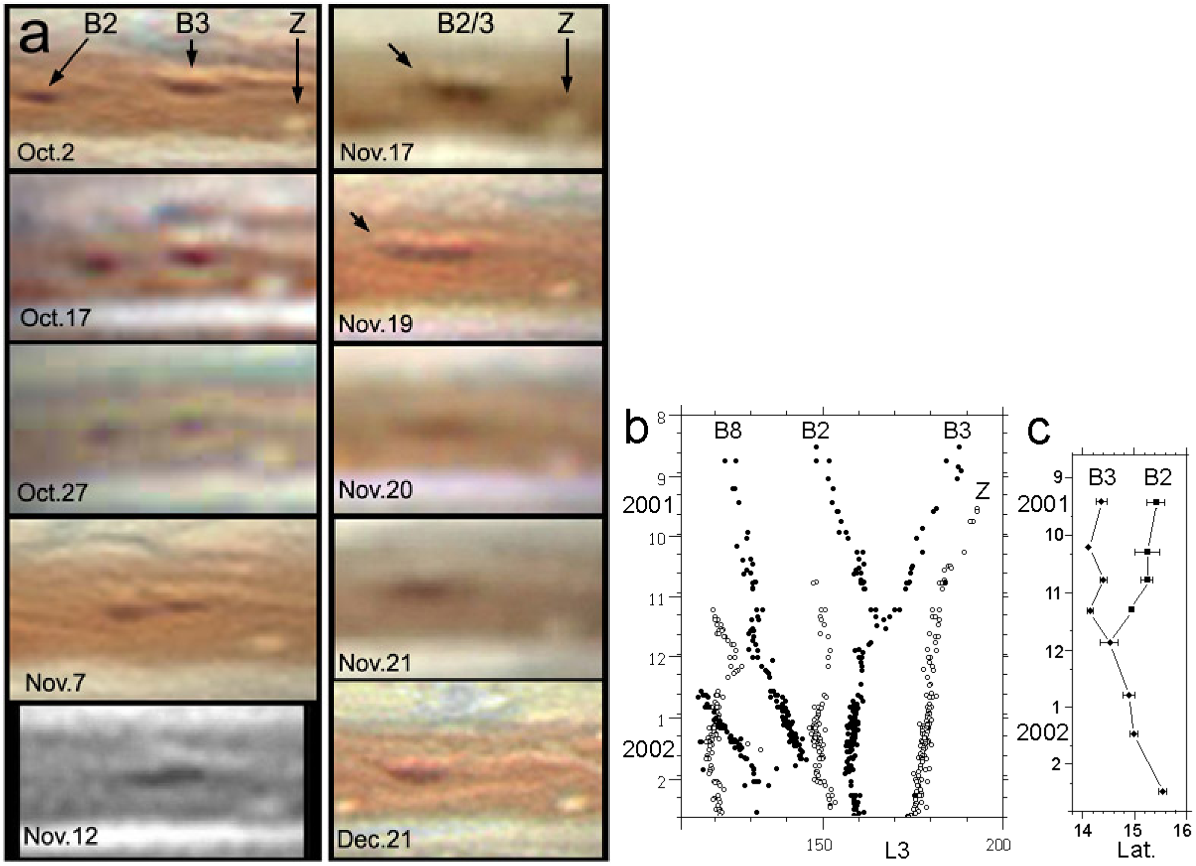


Fig.5. Approach and merger of barges B2 and B3 in the NEB, 2001.

(a) Images. Indicated are barges B2 and B3 and white spot Z. The oblique arrow on Nov.17 and 19 indicates how the dark locus of the eastern and southern barge, B3, appeared on the south-west side of barge B2 during the merger. Images were taken by the following observers: 2001 Oct.2, E. Grafton; Oct.17, D.C.Parker; Oct.27, T. Akutsu; Nov.7, E. Grafton; Nov.12, D.M. Moore; Nov.17, P.C. Sherrod; Nov.19, E. Grafton; Nov.20, T. Akutsu; Nov.21, P.C. Sherrod; Dec.21, E. Grafton.

(b) Longitude chart. Time scale in months, longitude scale in System III. Black symbols, dark spots from latitudes +14 to +16.5° (barges); open symbols, white spots from +17 to +20° (AWOs).

(c) Latitude chart. Means over 15-30 days are plotted, with standard error of the mean. Squares, B2; diamonds, B3 and the merged barge.

Fig.6

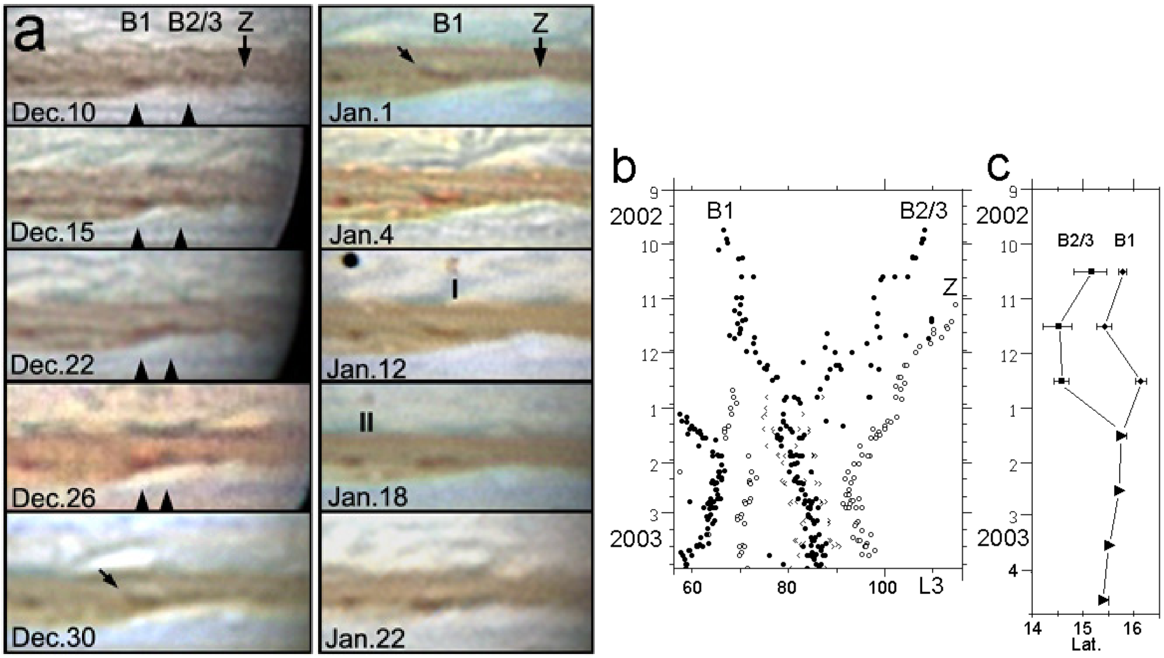


Fig.6. Approach and merger of barges B1 and B2/3 in the NEB, 2002/03.

(a) Images. Indicated are barges B2 and B3 and white spot Z. The oblique arrow on Dec.30 and Jan.1 indicates how the dark locus of the eastern and southern barge, B2/3, appeared on the south-west side of barge B1 during the merger. Images were taken by the following observers: 2002 Dec.10-22, D. Peach; Dec.26, D.C.Parker; Dec.30, P.C. Sherrod; 2003 Jan.1, D. Peach; Jan.4, E. Grafton; Jan.12, E.Ng (I indicates Io); Jan.18, D. Peach (II indicates Europa); Jan.22, E. Ng.

(b) Longitude chart. Time scale in months, longitude scale in System III. Black symbols, dark spots from latitudes +14 to +17° (barges); open symbols, white spots from +17 to +20° (AWOs).

(c) Latitude chart. Means over 30 days are plotted, with s.e.m. ($\leq$0.10° for the merged barge). Diamonds, B1; squares, B2/3; triangles, merged barge.

Fig.7

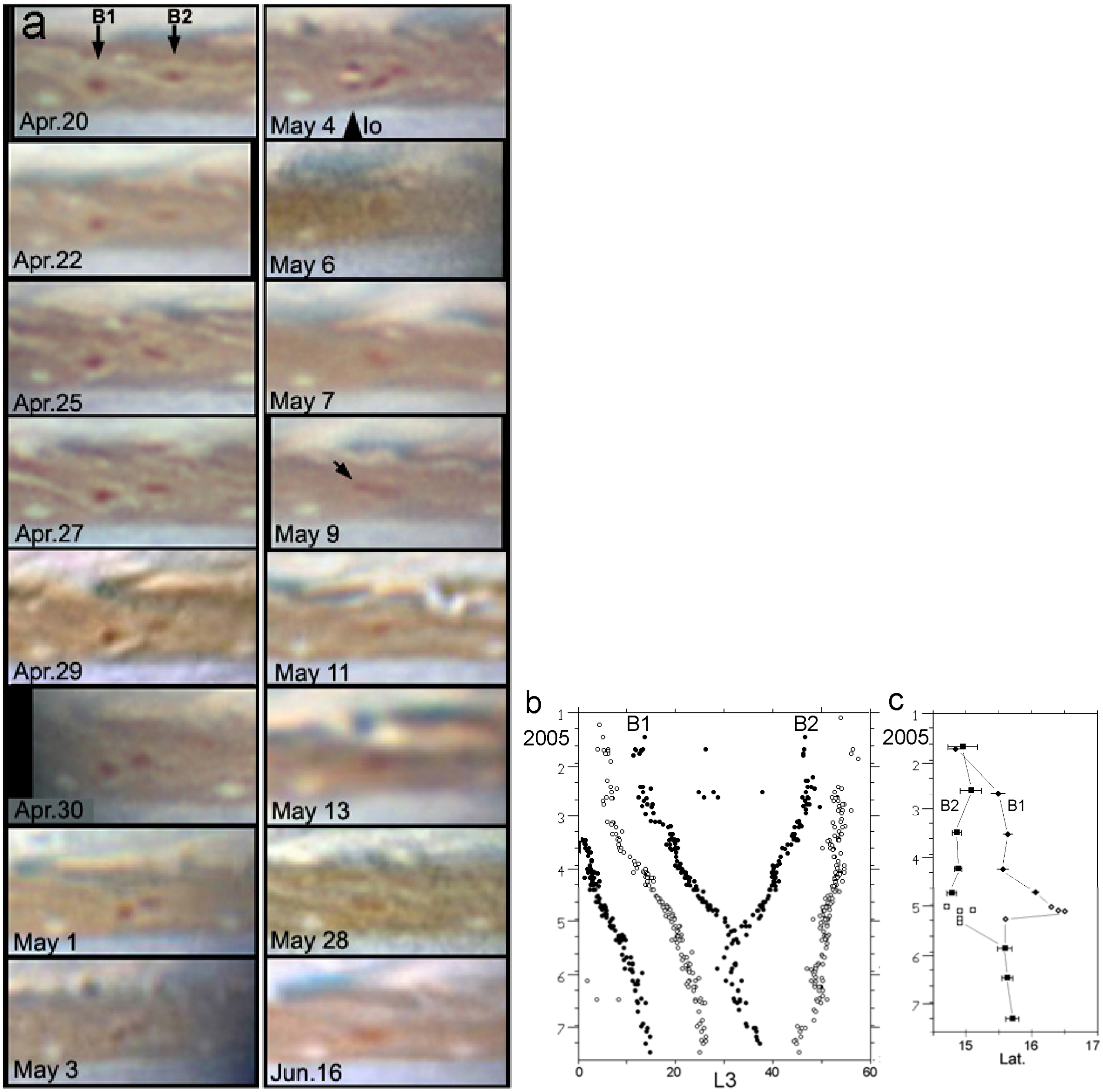


Fig. 7. Approach and merger of barges B1 and B2 in the NEB, 2005.

(a) Images. Arrowhead on May 4 indicates Io. The oblique arrow on May 9 indicates how the dark locus of the eastern and southern barge, B2, appeared on the south-west side of barge B1 during the merger. Images were taken by the following observers: D. Peach (April 20-27, April 30, May 4, 6, 9); I. Miyazaki (May 1, 3, 11); Z. Pujic (April 29); J.R. Sanchez (May 13); T. Akutsu and C. Go (May 28); D.C. Parker (June 16).

(b) Longitude chart. Time scale in months, longitude scale in System III. Black symbols, dark spots from latitudes +14 to +16.5° (barges); open symbols, white spots from +17 to +20° (AWOs).

(c) Latitude chart. Means over 15-30 days are plotted, with s.e.m. Open symbols are single measurements during the merger. Diamonds, B1; squares, B2 and merged barge.

Fig.8

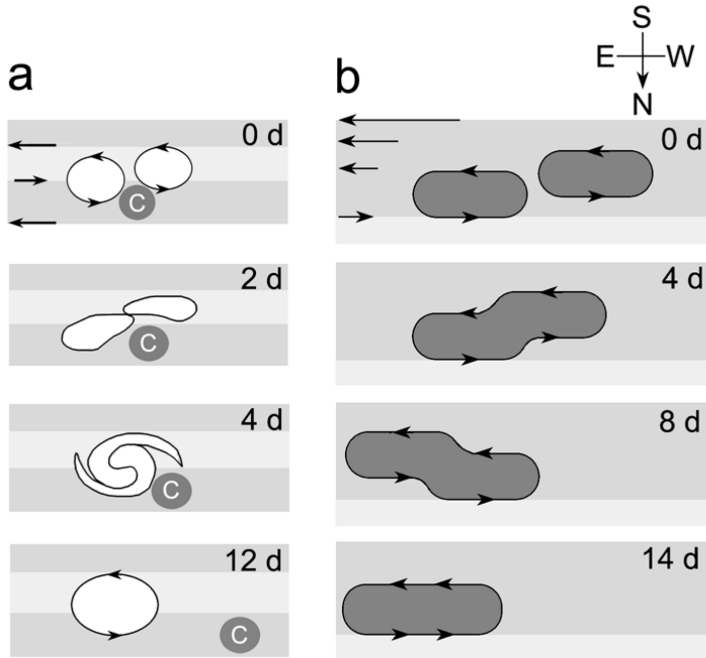


Fig. 8. Interpretative diagrams of the merger processes, with inferred currents.

(a) AWOs in S.S. Temperate region; (b) Cyclonic barges in NEB.

White and light grey areas are anticyclonic; darker grey areas are cyclonic.

The first panel in each set shows the directions of the zonal winds (not to scale).
