A MULTI-DISCIPLINARY INVESTIGATION OF THE JOVIAN SYSTEM

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Abstract

We emphasize the importance of treating Jupiter, its satellites and its magnetosphere as a system of mutual interactions and present a case for the multi-disciplinary investigation of that system. We point out (in a necessarily superficial way) the need for further measurements of

– Jupiter to constrain models of gas giant formation and interiors,
– Europa to understand its physical state and its potential for supporting life
– and Io and the magnetosphere to investigate physical processes which lead to the transport of material throughout the system.

We also discuss the feasibility of an Europe-only mission to the Jovian system and identify some key scientific experiments which would be needed for the investigation of the system.

Key words: Planets: Jupiter – Satellites: Europa

1. Introduction

The European Space Agency's programme must adapt to the changing nature of planetary sciences. Previously, planetary sciences was about discovery and an initial survey of our Solar System. However, the discovery of extrasolar planets (Mayor and Queloz 1995), the advances in astrobiology, and the increasing movement towards "exploration" requires a broader approach to satisfy a growing community. The planetary sciences programme must seek to establish which physical processes led to life on our planet and how probable they were.

Within the field of Solar System research, the European Space Agency's Science Programme has either successfully implemented or is currently implementing, missions to all the terrestrial planets (including the Earth), to moons of the Earth and Saturn, and to comets and asteroids. Paradoxically, the one reachable target which ESA's programme does not cover (the Jupiter system) contains two of the most scientifically (and publicly) exciting objects in our Solar System (Europa and Io) and a host of other interesting phenomena which will motivate enormous interest within the European scientific community and the public in general. The case for a detailed investigation of the Jovian system is extremely strong - a point which has also been made in the paper by Blanc et al. [this issue]. Here, we outline the justification for a multi-disciplinary approach. We base this upon two recent reference works, "Jupiter, The Planet, Satellites and Magnetosphere" edited by F. Bagenal et al. and "Europa, The Ocean Moon" by R. Greenberg. Following Atzei et al. (2003), we then suggest a method by which a European-only could be accomplished should an international collaboration prove not to be achievable.

2. Previous missions

Seven spacecraft have entered the Jovian system - Pioneer 10 and 11, Voyager 1 and 2, Ulysses, Galileo, and Cassini. The Voyager fly-bys in 1979 provided the first accurate survey of the Jovian system. They revealed the predicted activity of Io (Peale et al. 1979; Morabito et al. 1979), the young, icy surface of Europa (Greenberg 2005), the density and compositional distribution of plasma in the inner magnetosphere (Thomas et al. 2004), and detailed pictures of Jovian atmospheric dynamics (Ingersoll et al. 2004). This mission clearly established giant planet satellites as a major topic of interest in planetary science.

The Galileo mission was planned as the first giant planet orbiter and the first mission to send a probe into the atmosphere of a giant planet. It should have capitalised on the success of the Voyagers. As is well known, however, the mission did not run smoothly. It was delayed as a result of the loss of the Space Shuttle in Challenger in 1986 and when launched in 1989 the high gain antenna failed to open and the data rate from Jupiter was reduced to only 100 bit/s. These events had several consequences. Inevitably some of the experiments onboard were outdated. The plasma sciences experiment, for example, did not provide significant improvements over our knowledge from Voyager. The low data rate certainly affected the return from the major data rate consumers (the camera and the

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infrared spectrometer) reducing coverage enormously despite efforts to improve the onboard data compression and extensive use of the DSN's 70 m network.

The Galileo probe was highly successful but even here there have been difficulties in interpretation of the ammonia and water vapour measurements. It appears clear that the probe entered a hot spot in the atmosphere which leads to a need to study a cloudy zone in the atmosphere simply for comparative purposes (Taylor et al. 2004).

The Cassini fly-by in December 2000 has provided much complementary information about the Jovian system. The remarkable UV spectrometer observations of changes in the Io plasma torus over a 100 day period (Steffl et al. 2003) are an excellent example. But the fly-by was a relatively distant one, so that the most interesting observations of the system were remote sensing time series at lower spatial resolution and in situ magnetospheric measurements in the distant magnetosphere.

This is not to belittle the previous missions to the Jovian system - they have clearly brought major steps forward in our knowledge - but there remain many open questions which have been summarized in a recently published reference book about Jupiter (Bagenal et al. 2004). In the next section, we discuss a few of these in a little more detail.

3. Scientific themes

There are a large number of interesting phenomena in the Jovian system. Here we address three major themes and make a brief summary of several others which can capture the imagination.

3.1. Jupiter and planetary formation

Lunine et al. (2004) state that "modelling of the interior of Jupiter and compositional data have proceeded to the point where we can probably rule out the gravitational disk instability mechanism in favour of the nucleated instability (core accretion) mechanism for Jupiter". This is quite a remarkable statement about an object which has been observed for 400 years, visited by 7 spacecraft, and had a probe inserted into it down to the 20 bar level. Observations are pointing towards a large diversity of planetary systems. It is hard to imagine us reaching firm conclusions about the processes involved in producing this diversity unless we can explain adequately the formation of our own system. In order to do that, however, we have outstanding questions which must be answered and several of these can only be answered by in situ investigation.

For example, all heavy elements are enriched in Jupiter's atmosphere by a factor of about 3 relative to solar abundance (when expressed relative to hydrogen). How was this enrichment produced? The impact of small bodies such as comets would be an obvious answer except that comets do not contain nitrogen, carbon and sulphur in solar abundance and that the nitrogen isotope ratio ($^{15}N/^{14}N$) in Jupiter is rather low. The latter point indicates that nitrogen was brought to Jupiter in the form of N_2 because ion-molecule reactions in the interstellar medium tend to increase $^{15}N/^{14}N$ in molecules such as HCN. N_2 forms a minor fraction of the nitrogen inventory of comets (Lunine et al. 2004). If comets are not the source then what happened?

The entrance of the Galileo probe into a dry region ("hot spot") of Jupiter's atmosphere prevented assessment of the O/H ratio. Using remote sensing data in the 5 micron region, Roos-Serote et al. (2004) conclude that the global O/H ratio is at least 1 times the solar value. However, there remains considerable uncertainty without a detailed knowledge of the cloud structure in the troposphere down to the 10 bar level. With oxygen being one of the most abundant heavy elements, this too must be addressed to clarify the formation mechanism of the planet. Ideally, this requires a multi-probe system which could penetrate down to the 50-100 bar level (Taylor et al. 2004).

We are also uncertain about the size and structure of Jupiter's core. If the core accretion mechanism is correct, then an "embryo" is needed to form in the giant planet region of the solar nebula followed by accretion of gas onto this core. This process needed to be fast since we now know that the lifetime of any gaseous disc around the Sun was probably no more than 10 million years. A number of models have been produced which place some constraints on the mass of the initial "embryo". However, the absence of experimental data is beginning to hinder severely further progress. Jupiter's internal structure is rather poorly understood and hence experimental constraints are rather weak. Guillot et al. (2004) identify the accurate spatial mapping of the planet's magnetic and gravity fields as key measurements needed to determine the location at which helium demixing occurs, the existence of the phase transition boundary between molecular and metallic hydrogen, and the structure of the central core. To achieve this is a challenge since the requirements are to send a spacecraft or probe to within 3000 km of the cloud tops of the planet.

3.2. Europa and astrobiology

That most of the surface of Europa is covered by water ice was evident from the high geometric albedo and from ground-based spectrophotometry even before the Voyager fly-bys. But the observations by Voyager and Galileo have led to Europa becoming one of the most intriguing objects in the solar system. The surface is almost craterless and therefore extremely young - typically 50 million years or less. Such active re-surfacing demands a powerful mechanism.

The Laplace resonance of the three innermost Galilean satellites (Io, Europa, and Ganymede) combines with the tidal distortion produced by the presence of Jupiter to drive extensive volcanism on Io (Peale et al. 1979). An estimated 10^{14} W of heat is released through the friction inside the body. While the dissipation inside Europa is lower, it is by no means negligible, and it is estimated to be 6 x 10^{12} W. Thus, a heat flux of around 0.2 W m^{-2} and possibly more must pass through the surface layer (Greenberg 2005).

Europa has a bulk density of 3.01 g cm^{-3}. Its low moment of inertia indicates a differentiated interior. A three-layer model (Anderson et al. 1998) suggests that an ice shell of between 80 and 170 km thickness is required to explain the gravity data. This has led to the idea of Europa's surface being essentially an ice sheet covering a liquid ocean. The change in the magnetic moment of the satellite in phase with the changing sign of the radial field of Jupiter's magnetosphere also strongly suggests that there is a conducting salty ocean capable of carrying substantial electric currents under an ice shell (Zimmer et al. 2000). (We note in passing that the magnetometer on Galileo indicated that both Ganymede and Callisto may also have sub-surface oceans.)

The ice shell shows cracks and structures which are correlated with predicted stress patterns resulting from tidal flexure (Greenberg 2005). Where cracks have occurred ridges have formed. This has been interpreted as showing that water has recently risen between two plates and has flowed onto the surface before rapidly freezing. There are also areas of chaotic terrain which gives a strong impression of broken ice flows floating on a liquid which subsequently froze over again.

The present thickness of the ice layer is a subject of controversy with arguments for and against a thin ($<<$10 km) ice layer (cf. Greenberg 2005; Greeley et al. 2004). Hence, direct access to the ocean may not be straightforward and further investigation of the satellite is required. However, all the pre-requisites for the development of biotic material are available. Heat and water are present. Carbon and other elements, if not already existing on Europa at the time of its formation, can be transported there by magnetospheric processes and oxygen is available from the radiation bombardment of ice (see below). The comet Shoemaker-Levy 9 impact on Jupiter showed us that, even if these endogenic processes are insufficient, transport of long-chain hydrocarbons to Europa from outside the Jovian system has definitely occurred. The ice shell even provides a protective layer for the ocean against the harsh radiation environment in Jupiter's magnetosphere. Although radiation tolerant bacteria exist on Earth (e.g. D.radiodurans), it remains unclear whether life here started in a benign environment and evolved into extremophiles or vice versa. In any event, the conditions inside Europa are clearly tolerable for many bacteria. While the present conditions on Mars are rather sterile (at least there is no evidence of liquid water or copious amounts of oxygen at the surface), Europa has enough of both to support life now.

3.3. Io and the Jovian magnetosphere

Around 1 ton/s of material is ejected from Io as a result of the interaction of Jupiter's magnetosphere with Io's bizarre atmosphere. The discovery of volcanic activity on Io was one of the outstanding successes of the Voyager mission but the relationship of this volcanic activity to Io's atmosphere remains unclear. The atmosphere is mostly composed of SO_2 (McGrath et al. 2004) but this is also one of the gases which drives the volcanic activity and Doppler measurement of SO emission at microwave wavelengths (Lellouch et al. 1996) and HST measurements of gases above the volcanic vents (McGrath et al. 2000) suggest that much of the "atmosphere" is of direct volcanic origin.

Material is removed from the atmosphere by processes which we do not yet fully understand. Much, but not all, of the material forms a neutral cloud which surrounds Io and accompanies it in its orbit about Jupiter. This cloud undergoes electron impact ionization and charge-exchange to produce a dense plasma (up to 4000 electron cm^{-3}) called the Io plasma torus. Studies of the neutral cloud and the Io plasma torus reveal it to contain not merely sulphur, oxygen, and SO_2 but also sodium, potassium, and chlorine. At present limits on other species are not tight enough to rule out non-negligible amounts of other alkali metals, halogens, nitrogen, and silicon.

Once these ions are picked up by the Jovian magnetic field they slowly diffuse throughout Jupiter's magnetosphere and dominate its plasma population (Russell 2005). On reaching the outer magnetosphere, processes which again are only poorly understood lead some of the ions and electrons to precipitate along field lines to form Jupiter's prominent aurorae. Charge-exchange processes are also prevalent and produce fast neutrals which, unless a further collision occurs (with a satellite for example), leave the system.

The diffusing ions and fast neutrals can impact the surfaces of all of the solid bodies in the Jovian system. The ions, neutrals, and, perhaps importantly, the electrons produce a charged particle bombardment of Europa's surface which can itself lead to interesting processes. For example, ion and neutral implantation in Europa's surface ices provides additional species which can react with endogenic material. Hydrated alkali sulphates and chlorides are potential products. CO_2 has been observed as a gas trapped in ice on both Ganymede and Callisto. CO_2 has been seen as an atmospheric constituent on Callisto (Carlson 1999). If these species can be released by energetic particle impact and transported to Europa, we have a potential source of carbonates and complex hydrocarbons.

As pointed out by Johnson et al. (2004), these products will not remain at the surface for long. Upwelling of liquid water will "wash" this material off the surface and transport it into any sub-surface ocean. Subduction processes and re-surfacing will also occur. Meteoroid bombardment will increase this rate. If the ocean is within a few kilometres of the surface, it is inconceivable that these potential reactants (nutrients?) would not reach the ocean on fairly rapid timescales. Hence, even if Europa had started as a rocky core with a pure water ice mantle, it is now "contaminated" with elements which can combine to produce long chain molecules and perhaps more.

Irradiation of water ice can also result in the production of hydrogen peroxide and molecular oxygen through trapping of the hydroxyl radical (Johnson et al. 2004). O_2 has in fact been detected in Europa's atmosphere indirectly using HST through observation of the OI emission at 1304 Å and 1356 Å (Hall et al. 1995).

The investigation of Io and its effects on the Jovian magnetosphere and Europa demand development and use of updated experimental techniques. Examples might include again high resolution thermal imaging and laser altimetry of the satellite itself, microwave spectroscopy of its atmosphere, detailed compositional analysis of the plasma throughout the system, and UV spectroscopic monitoring of plasma and auroral emissions.

3.4. Other phenomena of interest

The atmospheric dynamics of Jupiter remain an enigma. Despite many years of study, we still lack fundamental understanding. The difficulty is that many of the phenomena we observe (banding, zonal jets, long-lived vortices) are probably linked to the composition, thermal structure and dynamics of the deep atmosphere down to the 100 bar level and beyond (Ingersoll et al. 2004). The upper aerosol layers are reasonably well understood (West et al. 2004) but even here questions exist concerning, for example, the polar stratospheric haze (which may been linked to the aurorae). This again provides a strong case for a multi-probe mission into the Jovian atmosphere but also for application of improving techniques in, for example, microwave spectroscopy from close orbiters and continued investigation of the link between, on the one hand, atmospheric and ionospheric chemistry, and on the other, energetic particle precipitation.

Ganymede is the largest planetary satellite in our solar system and exhibits some unusual properties. It appears to possess an intrinsic magnetic field which was first deduced from radio phenomena in the satellite's wake. The effects of this field have been imaged by HST through the auroral emissions of OI at 1356 Å (McGrath et al. 2004). The gravity data suggests a highly differentiated body with a hot and possibly molten iron core. There also appears to be shows an inductive component to the field similar to that of Europa which can also be interpreted in terms of a sub-surface ocean. The interaction of Jupiter's magnetosphere with this bizarre structure is clearly complex and remains poorly understood. The relationship of these phenomena to the appearance of younger, bright, terrain on the surface of Ganymede is not known.

Callisto is probably only partially differentiated. It possesses a tenuous atmosphere of CO_2 and, remarkably, also shows evidence of an induced magnetic field. If the same interpretation is adopted as for Europa and Ganymede, then Callisto, too, must have a conducting layer and liquid water would be a candidate. However, the heat source required to maintain such an "ocean" is not obvious since Callisto does not participate in the Laplace resonance.

3.5. Wider participation

A highly successful aspect of the Galileo mission was the development of a wide ranging ground-based and Earth-orbiting observational programme – the International Jupiter Watch. A similar programme associated with this mission concept would ensure a broad level of interest and support.

3.6. Summary

A programme dedicated to the investigation of the Jupiter system can answer major questions about planetary formation, biologically benign environments, and physical processes in our planetary system. The planetary and space sciences community in Europe can rarely look forward to more than one mission every 4 or so years (2003/4/5 have been exceptional - the gap between Venus Express and BepiColombo is 7 years) and hence it is vital that as many sub-disciplines as possible are actively engaged in one mission. The Jupiter system offers excellent opportunities for broad community participation.

4. Europe goes to Europa

4.1. International collaboration

The only previous ESA mission to the outer Solar System was the highly successful Huygens probe to Titan which was carried to Saturn by NASA's Cassini spacecraft. This collaboration has been hugely successful and could form a model for further ESA exploration of the Jupiter system. In recent years, however, international collaboration does not appear to have been high on NASA's agenda. Furthermore, NASA has, until recently, been exploring nuclear powered solutions for Jupiter exploration which many scientists both in Europe and the US have considered unrealistic in the current financial climate.

Although the political situation in NASA has changed with the cancellation of JIMO and the appearance of collaborative noises from Washington, it is important to note that ESA may well be capable of launching missions to Jupiter without any international collaboration at all. Inevitably a collaboration with NASA would make more resources available for a Jupiter mission and there is no doubt that a European-only mission to Jupiter would have severe technical problems to overcome. Nonetheless studies show that ESA could put together a perfectly acceptable Jupiter programme within challenging but possibly feasible technical and financial constraints. We explore this possibility in the next sub-sections.

4.2. A European-only mission

The Jupiter Minisat Orbiter (JMO) concept has been discussed in Atzei et al. (2003) and has been the subject of an ESA study. The major problem with any mission to Jupiter is the harsh radiation environment. The JMO concept overcomes this by the use of a relay satellite (JRS) which remains in a (relatively) benign orbit in the outer magnetosphere. The detailed studies of the system are completed by small probes which are targetted at specific objectives. The relatively short design lifetime of the probes (e.g. 60 days in orbit about Europa) allows us to constrain the technological development needed to withstand the radiation and hence constrain cost.

Targets for the probes are numerous in the Jupiter system. We could envisage

- A short-lived (60 day) Europa orbiter
- A longer-lived Ganymede or Callisto orbiter
- A multiple fly-by probe for Io
- One or more Jupiter atmospheric probes
- One or more magnetospheric probes (possibly into polar regions)

It is clear that the JRS can also perform top quality science. The spacecraft peri-jove might be set close to the region in Jupiter's magnetosphere which forms the source of Jupiter's aurorae. One could also imagine devising a Jovicentric orbit in resonance with the orbit of either Ganymede or Callisto. This needs to be investigated in a detailed study. The JRS can then monitor Jupiter's atmosphere and magnetospheric phenomena at high resolution during a mission lasting long after the loss of the probe(s). It is also conceivable that a second launch could occur, taking advantage of the existing JRS, carrying several more probes (potentially even from another space agency) which would then add enormously to the scientific return and produce an entire Jupiter system programme within a relatively short time.

It should be noted that we have not mentioned the idea of a Europa lander. Within an ESA-only programme, it is likely that any Europa lander concept would be eliminated by cost considerations (cf. BepiColombo). However, in the event of an NASA-ESA collaboration this may be worthwhile revisiting. We note however that not only will it be hard to determine how to land on the surface but also, considering the limited information from Galileo, the issue of where to land will make mission definition difficult and potentially costly.

4.3. Potential payloads

A payload was also discussed as past of ESA's JMO study. However, we suggest here some alternative ideas.

For the JRS, the following instruments need to be considered (with instruments with similar specifications - although generally much heavier than can be flown here - in parentheses):

- An ultraviolet imaging spectrometer (λ=800Å-2500 Å; $\Delta\lambda$=0.1 Å) (Cassini/UVIS)
- In situ plasma diagnostics package (Rosetta/RPC)
- A microwave spectrometer (Rosetta/MIRO)

The UVIS would provide continuous monitoring of the auroral emissions from Jupiter and the Galilean satellites as well as the magnetospheric emissions of the Io plasma torus. The plasma diagnostics package would complement this by providing ion composition (up to molecular weight 200), ion and electron energy distribution functions (including highly energetic species), magnetic field strength, and energetic neutral analysis. The microwave spectrometer would prove spatially resolved measurements of Jupiter's atmospheric composition and 3-D atmospheric temperature distribution. It would also attempt to place constraints on the densities and distributions of water vapour in the satellite "atmosphere".

In the event of the JRS completing Ganymede or Callisto fly-bys, these instruments need to be supported by radio science and a high resolution imaging system.

A great advantage of the multi-probe approach is that the payload can be optimized for each target. In Table 1 we give a number of examples of possible payload combinations. This is by no means comprehensive and differs substantially from that proposed in Atzei et al. (2003) but illustrates the possibilities. It should be noted that each individual instrument can itself be optimized for the specific environment it will face. Hence, although there is experience with most instruments, modification, adaptation, and optimization will greatly enhance the scientific return.

Of the experiments mentioned, the need for a thermal infrared camera for a planetary mission is clearly of note. For Rosetta, the claims for some form of thermal emission system were rejected in favour of extending the visible and infrared spectrometer out to 5 microns. The determination of the heat flux from Io and the search for temperature variations over the Europan surface (possibly indicating shallow liquid) suggest that spatially resolved temperature measurements are required at high relative and absolute accuracy down to temperatures of 87 K or less. Furthermore, the thermal emission spectrometers (TES) onboard Mars Global Surveyor and the Mars Exploration Rovers have shown the advantages for mineral identification of working in the 5-20 micron range. However, at present the only example of this type of experiment in development for a European planetary mission (to our knowledge) is the MERTIS experiment for BepiColombo which is in a very preliminary state of development.

Table 1. Possible instruments for mini-satellites in a JMO mission.

	Europa Orbiter	Io fly-by	Jupiter probe	Ganymede Orbiter	Possible heritage
High-res camera	X	X		X	
Low-res camera			X		VEX/VMC and Huygens/DISR
Visible IR spec.	X	X		X	Rosetta/VIRTIS
Thermal IR cam/spec	X	X		X	BPC/MERTIS
Radar sounder	X				MEX/MARSIS
Laser altimeter	X			X	BPC/BELA
Ion and neutral MS	X	X	X	X	Rosetta/ROSINA
GC			X		Philae/COSAC
Aerosol analyser			X		Huygens/ACP
P,n,T sensors			X		Huygens/HASI
Radio science	X	X		X	BpC/MORE
Magnetometer	X	X		X	VEX/MAG
Plasma diagnostics	X	X		X	Rosetta/RPC

4.4. Technology issues

It has been assumed until recently that a mission to Jupiter is not possible within a European context because ESA lacks access to radioisotope thermal generator (RTG) technology. While this situation may be changing, there is no doubt that RTGs remain politically sensitive. It must also be considered that RTG development is hugely expensive and it is arguable whether ESA can use RTGs frequently enough to make the initial investment pay-off. However, recent developments in solar cell technology and the existence of solar concentrators makes the possibility of a mission to Jupiter without RTGs conceivable as has been shown in the JMO study.

The failure of Galileo's high gain antenna emphasized the importance of data rate in outer Solar System missions. The opening of the New Norcia station allows Europeans to think about getting higher data volumes back from Jupiter. Furthermore, optical (laser) communications are getting to a stage where practical applications in deep space communication can be considered.

Spacecraft and payload miniaturization remain challenging. The payload complements of the mini-satellites for JMO are small even by the standards of SMART-1 with total payload mass less than half of a single instrument on Mars Express. The issue will resolve itself into a trade-off between paying for a more powerful launcher, the cost of miniaturization, and the descoping of instrumentation and instrument performance to meet the mass margin. In any event, ESA and the member states would be well advised to allocate financing to prepare breadboards (not just paper studies) prior to any instrument selection for such a mission. Similar investments on the spacecraft side will also be beneficial.

Inevitably, radiation tolerance is the most challenging problem. A 60 day mission around Europa will require tolerance to over 2 Mrad with 4 mm of shielding. But even here progress is already being made. The BepiColombo and Solar Orbiter missions both have difficult radiation requirements and development of the spacecraft and payloads for these missions need to pay careful attention to radiation tolerance.

There are technical difficulties to this concept but there are no obvious technical showstoppers for the implementation of a mission of this type within the 10-15 years. Even in the event of a future joint NASA-ESA mission, studies of instrumentation for both payload and spacecraft along these lines will not be wasted.

5. Conclusions

A multi-disciplinary investigation of the Jupiter system comprising

- observations to constrain the Jovian formation mechanism
- investigations of Europa's physical state and its ability to support life
- studies of other processes which have bearing on the evolution of the system

is a logical next step in our exploration of our Solar System. It complements studies of extra-solar planet formation and astrobiology while at the same time engaging the existing strong communities in planetary and space sciences.

While a joint NASA-ESA mission, following the Cassini-Huygens model, is attractive we also point out that Europe is technically in a position to initiate a high quality Jupiter programme itself. Should international collaboration prove to be too difficult to agree then there is no strong reason not to go it alone. Whichever approach is ultimately selected **Europe can and should go to Europa.**

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