= Rings of Jupiter =

The planet Jupiter has a system of rings known as the rings of Jupiter or the Jovian ring system . It was the third ring system to be discovered in the Solar System , after those of Saturn and Uranus . It was first observed in 1979 by the Voyager 1 space probe and thoroughly investigated in the 1990s by the Galileo orbiter . It has also been observed by the Hubble Space Telescope and from Earth for the past 23 years . Ground @-@ based observations of the rings require the largest available telescopes .

The Jovian ring system is faint and consists mainly of dust . It has four main components : a thick inner torus of particles known as the " halo ring " ; a relatively bright , exceptionally thin " main ring " ; and two wide , thick and faint outer " gossamer rings " , named for the moons of whose material they are composed : Amalthea and Thebe .

The main and halo rings consist of dust ejected from the moons Metis , Adrastea , and other unobserved parent bodies as the result of high @-@ velocity impacts . High @-@ resolution images obtained in February and March 2007 by the New Horizons spacecraft revealed a rich fine structure in the main ring .

In visible and near @-@ infrared light , the rings have a reddish color , except the halo ring , which is neutral or blue in color . The size of the dust in the rings varies , but the cross @-@ sectional area is greatest for nonspherical particles of radius about 15 ?m in all rings except the halo . The halo ring is probably dominated by submicrometre dust . The total mass of the ring system (including unresolved parent bodies) is poorly known , but is probably in the range of 1011 to 1016 kg . The age of the ring system is not known , but it may have existed since the formation of Jupiter .

A ring could possibly exist in Himalia 's orbit . One possible explanation is that a small moon had crashed into Himalia and the force of the impact caused material to blast off Himalia .

= = Discovery and structure = =

Jupiter 's ring system was the third to be discovered in the Solar System , after those of Saturn and Uranus . It was first observed in 1979 by the Voyager 1 space probe . It comprises four main components : a thick inner torus of particles known as the " halo ring " ; a relatively bright , exceptionally thin " main ring " ; and two wide , thick and faint outer " gossamer rings " , named after the moons of whose material they are composed : Amalthea and Thebe . The principal attributes of the known Jovian Rings are listed in the table .

= = Main ring = =

= = = Appearance and structure = = =

The narrow and relatively thin main ring is the brightest part of Jupiter 's ring system . Its outer edge is located at a radius of about 129000 km (1 @.@ 806 RJ ; RJ = equatorial radius of Jupiter or 71398 km) and coincides with the orbit of Jupiter 's smallest inner satellite , Adrastea . Its inner edge is not marked by any satellite and is located at about 122500 km (1 @.@ 72 RJ) .

Thus the width of the main ring is around 6500 km . The appearance of the main ring depends on the viewing geometry . In forward @-@ scattered light the brightness of the main ring begins to decrease steeply at 128600 km (just inward of the Adrastean orbit) and reaches the background level at 129300 km ? just outward of the Adrastean orbit . Therefore , Adrastea at 129000 km clearly shepherds the ring . The brightness continues to increase in the direction of Jupiter and has a maximum near the ring ? s center at 126000 km , although there is a pronounced gap (notch) near the Metidian orbit at 128000 km . The inner boundary of the main ring , in contrast , appears to fade off slowly from 124000 to 120000 km , merging into the halo ring . In forward @-@ scattered light all Jovian rings are especially bright .

In back @-@ scattered light the situation is different . The outer boundary of the main ring , located at 129100 km , or slightly beyond the orbit of Adrastea , is very steep . The orbit of the moon is marked by a gap in the ring so there is a thin ringlet just outside its orbit . There is another ringlet just inside Adrastean orbit followed by a gap of unknown origin located at about 128500 km . The third ringlet is found inward of the central gap , outside the orbit of Metis . The ring ? s brightness drops sharply just outward of the Metidian orbit , forming the Metis notch . Inward of the orbit of Metis , the brightness of the ring rises much less than in forward @-@ scattered light . So in the back @-@ scattered geometry the main ring appears to consist of two different parts : a narrow outer part extending from 128000 to 129000 km , which itself includes three narrow ringlets separated by notches , and a fainter inner part from 122500 to 128000 km , which lacks any visible structure like in the forward @-@ scattering geometry . The Metis notch serves as their boundary . The fine structure of the main ring was discovered in data from the Galileo orbiter and is clearly visible in back @-@ scattered images obtained from New Horizons in February ? March 2007 . The early observations by Hubble Space Telescope (HST) , Keck and the Cassini spacecraft failed to detect it , probably due to insufficient spatial resolution . However the fine structure was observed by the Keck telescope using adaptive optics in 2002 ? 2003 .

Observed in back @-@ scattered light the main ring appears to be razor thin , extending in the vertical direction no more than 30 km . In the side scatter geometry the ring thickness is 80 ? 160 km , increasing somewhat in the direction of Jupiter . The ring appears to be much thicker in the forward @-@ scattered light ? about 300 km . One of the discoveries of the Galileo orbiter was the bloom of the main ring ? a faint , relatively thick (about 600 km) cloud of material which surrounds its inner part . The bloom grows in thickness towards the inner boundary of the main ring , where it transitions into the halo .

Detailed analysis of the Galileo images revealed longitudinal variations of the main ring ? s brightness unconnected with the viewing geometry . The Galileo images also showed some patchiness in the ring on the scales 500 ? 1000 km .

In February ? March 2007 New Horizons spacecraft conducted a deep search for new small moons inside the main ring . While no satellites larger than 0 @.@ 5 km were found , the cameras of the spacecraft detected seven small clumps of ring particles . They orbit just inside the orbit of Adrastea inside a dense ringlet . The conclusion , that they are clumps and not small moons , is based on their azimuthally extended appearance . They subtend 0 @.@ 1 ? 0 @.@ 3 ° along the ring , which correspond to 1000 ? 3000 km . The clumps are divided into two groups of five and two members , respectively . The nature of the clumps is not clear , but their orbits are close to 115 : 116 and 114 : 115 resonances with Metis . They may be wavelike structures excited by this interaction .

= = = Spectra and particle size distribution = = =

Spectra of the main ring obtained by the HST , Keck , Galileo and Cassini have shown that particles forming it are red , i.e. their albedo is higher at longer wavelengths . The existing spectra span the range 0 @.@ 5 ? 2 @.@ 5 ?m . No spectral features have been found so far which can be attributed to particular chemical compounds , although the Cassini observations yielded evidence for absorption bands near 0 @.@ 8 ?m and 2 @.@ 2 ?m . The spectra of the main ring are very similar to Adrastea and Amalthea .

The properties of the main ring can be explained by the hypothesis that it contains significant amounts of dust with 0 @.@ 1 ? 10 ?m particle sizes . This explains the stronger forward @-@ scattering of light as compared to back @-@ scattering . However , larger bodies are required to explain the strong back @-@ scattering and fine structure in the bright outer part of the main ring .

Analysis of available phase and spectral data leads to a conclusion that the size distribution of small particles in the main ring obeys a power law

<formula>

where n (r) dr is a number of particles with radii between r and r + dr and <formula> is a normalizing parameter chosen to match the known total light flux from the ring . The parameter q is 2 @.@ 0 ± 0 @.@ 2 for particles with r < 15 ± 0 @.@ 3 ?m and q = 5 ± 1 for those with r > 15 ± 0 @.@ 3 ?m . The distribution of large bodies in the mm ? km size range is undetermined presently .

The light scattering in this model is dominated by particles with r around 15 ?m .
The power law mentioned above allows estimation of the optical depth <formula> of the main ring : <formula> for the large bodies and <formula> for the dust . This optical depth means that the total cross section of all particles inside the ring is about 5000 km ^{2} . The particles in the main ring are expected to have aspherical shapes . The total mass of the dust is estimated to be 107 ? 109 kg . The mass of large bodies , excluding Metis and Adrastea , is 1011 ? 1016 kg . It depends on their maximum size ? the upper value corresponds to about 1 km maximum diameter . These masses can be compared with masses of Adrastea , which is about 2 × 1015 kg , Amalthea , about 2 × 1018 kg , and Earth 's Moon , 7 @.@ 4 × 1022 kg .
The presence of two populations of particles in the main ring explains why its appearance depends on the viewing geometry . The dust scatters light preferably in the forward direction and forms a relatively thick homogenous ring bounded by the orbit of Adrastea . In contrast , large particles , which scatter in the back direction , are confined in a number of ringlets between the Metidian and Adrastean orbits .

= = = Origin and age = = =

The dust is constantly being removed from the main ring by a combination of Poynting ? Robertson drag and electromagnetic forces from the Jovian magnetosphere . Volatile materials , for example ices , evaporate quickly . The lifetime of dust particles in the ring is from 100 to 1000 years , so the dust must be continuously replenished in the collisions between large bodies with sizes from 1 cm to 0 @.@ 5 km and between the same large bodies and high velocity particles coming from outside the Jovian system . This parent body population is confined to the narrow ? about 1000 km ? and bright outer part of the main ring , and includes Metis and Adrastea . The largest parent bodies must be less than 0 @.@ 5 km in size . The upper limit on their size was obtained by New Horizons spacecraft . The previous upper limit , obtained from HST and Cassini observations , was near 4 km . The dust produced in collisions retains approximately the same orbital elements as the parent bodies and slowly spirals in the direction of Jupiter forming the faint (in back @-@ scattered light) innermost part of the main ring and halo ring . The age of the main ring is currently unknown , but it may be the last remnant of a past population of small bodies near Jupiter .

= = = Vertical corrugations = = =

Images from the Galileo and New Horizons space probes show the presence of two sets of spiraling vertical corrugations in the main ring . These waves became more tightly wound over time at the rate expected for differential nodal regression in Jupiter 's gravity field . Extrapolating backwards , the more prominent of the two sets of waves appears to have been excited in 1995 , around the time of the impact of Comet Shoemaker @-@ Levy 9 with Jupiter , while the smaller set appears to date to the first half of 1990 . Galileo 's November 1996 observations are consistent with wavelengths of 1920 ± 150 and 630 ± 20 km , and vertical amplitudes of 2 @.@ 4 ± 0 @.@ 7 and 0 @.@ 6 ± 0 @.@ 2 km , for the larger and smaller sets of waves , respectively . The formation of the larger set of waves can be explained if the ring was impacted by a cloud of particles released by the comet with a total mass on the order of 2 ? 5 × 1012 kg , which would have tilted the ring out of the equatorial plane by 2 km . A similar spiraling wave pattern that tightens over time has been observed by Cassini in Saturns 's C and D rings .

= = Halo ring = =

= = = Appearance and structure = = =

The halo ring is the innermost and the vertically thickest Jovian ring . Its outer edge coincides with the inner boundary of the main ring approximately at the radius 122500 km (1 @.@ 72 RJ) . From this radius the ring becomes rapidly thicker towards Jupiter . The true vertical extent of the halo is not known but the presence of its material was detected as high as 10000 km over the ring plane . The inner boundary of the halo is relatively sharp and located at the radius 100000 km (1 @.@ 4 RJ) , but some material is present further inward to approximately 92000 km . Thus the width of the halo ring is about 30000 km . Its shape resembles a thick torus without clear internal structure . In contrast to the main ring , the halo 's appearance depends only slightly on the viewing geometry .

The halo ring appears brightest in forward @-@ scattered light , in which it was extensively imaged by Galileo . While its surface brightness is much less than that of the main ring , its vertically (perpendicular to the ring plane) integrated photon flux is comparable due to its much larger thickness . Despite a claimed vertical extent of more than 20000 km , the halo ? s brightness is strongly concentrated towards the ring plane and follows a power law of the form z ? 0 @.@ 6 to z ? 1 @.@ 5 , where z is altitude over the ring plane . The halo ? s appearance in the back @-@ scattered light , as observed by Keck and HST , is the same . However its total photon flux is several times lower than that of the main ring and is more strongly concentrated near the ring plane than in the forward @-@ scattered light .

The spectral properties of the halo ring are different from the main ring . The flux distribution in the range 0 @.@ 5 ? 2 @.@ 5 ?m is flatter than in the main ring ; the halo is not red and may even be blue .

= = = Origin of the halo ring = = =

The optical properties of the halo ring can be explained by the hypothesis that it comprises only dust with particle sizes less than 15 ?m . Parts of the halo located far from the ring plane may consist of submicrometre dust . This dusty composition explains the much stronger forward @-@ scattering , bluer colors and lack of visible structure in the halo . The dust probably originates in the main ring , a claim supported by the fact that the halo ? s optical depth <formula> is comparable with that of the dust in the main ring . The large thickness of the halo can be attributed to the excitation of orbital inclinations and eccentricities of dust particles by the electromagnetic forces in the Jovian magnetosphere . The outer boundary of the halo ring coincides with location of a strong 3 : 2 Lorentz resonance . As Poynting ? Robertson drag causes particles to slowly drift towards Jupiter , their orbital inclinations are excited while passing through it . The bloom of the main ring may be a beginning of the halo . The halo ring ? s inner boundary is not far from the strongest 2 : 1 Lorentz resonance . In this resonance the excitation is probably very significant , forcing particles to plunge into the Jovian atmosphere thus defining a sharp inner boundary . Being derived from the main ring , the halo has the same age .

= = Gossamer rings = =

= = = Amalthea gossamer ring = = =

The Amalthea gossamer ring is a very faint structure with a rectangular cross section , stretching from the orbit of Amalthea at 182000 km (2 @.@ 54 RJ) to about 129000 km (1 @.@ 80 RJ) . Its inner boundary is not clearly defined because of the presence of the much brighter main ring and halo . The thickness of the ring is approximately 2300 km near the orbit of Amalthea and slightly decreases in the direction of Jupiter . The Amalthea gossamer ring is actually the brightest near its top and bottom edges and becomes gradually brighter towards Jupiter ; one of the edges is often brighter than another . The outer boundary of the ring is relatively steep ; the ring 's brightness drops abruptly just inward of the orbit of Amalthea , although it may have a small extension beyond the orbit of the satellite ending near 4 : 3 resonance with Thebe . In forward @-@ scattered light the ring appears to be about 30 times fainter than the main ring . In back @-@ scattered light it has been detected only by the Keck telescope and the ACS (Advanced Camera for Surveys) on HST . Back @-@ scattering images show additional structure in the ring : a peak in the brightness just inside the

Amalthean orbit and confined to the top or bottom edge of the ring .
In 2002 ? 2003 Galileo spacecraft had two passes through the gossamer rings . During them its dust counter detected dust particles in the size range 0 @.@ 2 ? 5 ?m . In addition , the Galileo spacecraft 's star scanner detected small , discrete bodies (< 1 km) near Amalthea . These may represent collisional debris generated from impacts with this satellite .
The detection of the Amalthea gossamer ring from the ground , in Galileo images and the direct dust measurements have allowed the determination of the particle size distribution , which appears to follow the same power law as the dust in the main ring with q = 2 ± 0 @.@ 5 . The optical depth of this ring is about 10 ? 7 , which is an order of magnitude lower than that of the main ring , but the total mass of the dust (107 ? 109 kg) is comparable .

= = = Thebe gossamer ring = = =

The Thebe gossamer ring is the faintest Jovian ring . It appears as a very faint structure with a rectangular cross section , stretching from the Thebean orbit at 226000 km (3 @.@ 11 RJ) to about 129000 km (1 @.@ 80 RJ ;) . Its inner boundary is not clearly defined because of the presence of the much brighter main ring and halo . The thickness of the ring is approximately 8400 km near the orbit of Thebe and slightly decreases in the direction of the planet . The Thebe gossamer ring is brightest near its top and bottom edges and gradually becomes brighter towards Jupiter ? much like the Amalthea ring . The outer boundary of the ring is not especially steep , stretching over 15000 km . There is a barely visible continuation of the ring beyond the orbit of Thebe , extending up to 280000 km (3 @.@ 75 RJ) and called the Thebe Extension . In forward @-@ scattered light the ring appears to be about 3 times fainter than the Amalthea gossamer ring . In back @-@ scattered light it has been detected only by the Keck telescope . Back @-@ scattering images show a peak of brightness just inside the orbit of Thebe . In 2002 ? 2003 the dust counter of the Galileo spacecraft detected dust particles in the size range 0 @.@ 2 ? 5 ?m ? similar to those in the Amalthea ring ? and confirmed the results obtained from imaging .
The optical depth of the Thebe gossamer ring is about 3 × 10 ? 8 , which is three times lower than the Amalthea gossamer ring , but the total mass of the dust is the same ? about 107 ? 109 kg . However the particle size distribution of the dust is somewhat shallower than in the Amalthea ring . It follows a power law with q < 2 . In the Thebe extension the parameter q may be even smaller .

= = = Origin of the gossamer rings = = =

The dust in the gossamer rings originates in essentially the same way as that in the main ring and halo . Its sources are the inner Jovian moons Amalthea and Thebe respectively . High velocity impacts by projectiles coming from outside the Jovian system eject dust particles from their surfaces . These particles initially retain the same orbits as their moons but then gradually spiral inward by Poynting ? Robertson drag . The thickness of the gossamer rings is determined by vertical excursions of the moons due to their nonzero orbital inclinations . This hypothesis naturally explains almost all observable properties of the rings : rectangular cross @-@ section , decrease of thickness in the direction of Jupiter and brightening of the top and bottom edges of the rings .
However some properties have so far gone unexplained , like the Thebe Extension , which may be due to unseen bodies outside Thebe 's orbit , and structures visible in the back @-@ scattered light . One possible explanation of the Thebe Extension is influence of the electromagnetic forces from the Jovian magnetosphere . When the dust enters the shadow behind Jupiter , it loses its electrical charge fairly quickly . Since the small dust particles partially corotate with the planet , they will move outward during the shadow pass creating an outward extension of the Thebe gossamer ring . The same forces can explain a dip in the particle distribution and ring 's brightness , which occurs between the orbits of Amalthea and Thebe .
The peak in the brightness just inside of the Amalthea 's orbit and , therefore , the vertical asymmetry the Amalthea gossamer ring may be due to the dust particles trapped at the leading (L4) and trailing (L5) Lagrange points of this moon . The particles may also follow horseshoe orbits

between the Lagrangian points . The dust may be present at the leading and trailing Lagrange points of Thebe as well . This discovery implies that there are two particle populations in the gossamer rings : one slowly drifts in the direction of Jupiter as described above , while another remains near a source moon trapped in 1 : 1 resonance with it .

= = Himalia ring = =

The small moon Dia , 4 kilometres in diameter , had gone missing since its discovery in 2000 . One theory is that it has crashed into the much larger moon Himalia , 170 kilometres in diameter , creating a faint ring . This possible ring appears as a faint streak near Himalia in images from NASA 's New Horizons mission to Pluto . This suggests that Jupiter sometimes gains and loses small moons through collisions . However , the recovery of Dia in 2010 and 2011 disproves the link between Dia and the Himalia ring , although it is still possible that a different moon may have been involved .

= = Exploration = =

The existence of the Jovian rings was inferred from observations of the planetary radiation belts by Pioneer 11 spacecraft in 1975 . In 1979 the Voyager 1 spacecraft obtained a single overexposed image of the ring system . More extensive imaging was conducted by Voyager 2 in the same year , which allowed rough determination of the ring ? s structure . The superior quality of the images obtained by the Galileo orbiter between 1995 and 2003 greatly extended the existing knowledge about the Jovian rings . Ground @-@ based observation of the rings by the Keck telescope in 1997 and 2002 and the HST in 1999 revealed the rich structure visible in back @-@ scattered light . Images transmitted by the New Horizons spacecraft in February ? March 2007 allowed observation of the fine structure in the main ring for the first time . In 2000 , the Cassini spacecraft en route to Saturn conducted extensive observations of the Jovian ring system . Future missions to the Jovian system will provide additional information about the rings .