= Rings of Uranus =

The planet Uranus has a system of rings intermediate in complexity between the more extensive set around Saturn and the simpler systems around Jupiter and Neptune . The rings of Uranus were discovered on March 10 , 1977 , by James L. Elliot , Edward W. Dunham , and Jessica Mink . More than 200 years ago , in 1789 , William Herschel also reported observing rings ; some modern astronomers are skeptical that he could have actually seen them , as they are very dark and faint ? others are not .
By 1978 , nine distinct rings were identified . Two additional rings were discovered in 1986 in images taken by the Voyager 2 spacecraft , and two outer rings were found in 2003 ? 2005 in Hubble Space Telescope photos . In the order of increasing distance from the planet the 13 known rings are designated 1986U2R / ? , 6 , 5 , 4 , ? , ? , ? , ? , ? , ? , ? , ? and ? . Their radii range from about 38 @,@ 000 km for the 1986U2R / ? ring to about 98 @,@ 000 km for the ? ring . Additional faint dust bands and incomplete arcs may exist between the main rings . The rings are extremely dark ? the Bond albedo of the rings ' particles does not exceed 2 % . They are probably composed of water ice with the addition of some dark radiation @-@ processed organics .
The majority of Uranus 's rings are opaque and only a few kilometers wide . The ring system contains little dust overall ; it consists mostly of large bodies 0 @.@ 2 ? 20 m in diameter . However , some rings are optically thin : the broad and faint 1986U2R / ? , ? and ? rings are made of small dust particles , while the narrow and faint ? ring also contains larger bodies . The relative lack of dust in the ring system is due to aerodynamic drag from the extended Uranian exosphere ? corona .

The rings of Uranus are thought to be relatively young , at not more than 600 million years old . The Uranian ring system probably originated from the collisional fragmentation of a number of moons that once existed around the planet . After colliding , the moons probably broke up into numerous particles , which survived as narrow and optically dense rings only in strictly confined zones of maximum stability .
The mechanism that confines the narrow rings is not well understood . Initially it was assumed that every narrow ring had a pair of nearby shepherd moons corralling them into shape . However , in 1986 Voyager 2 discovered only one such shepherd pair (Cordelia and Ophelia) around the brightest ring (11 rings) .

= = Discovery = =

The first mention of a Uranian ring system comes from William Herschel 's notes detailing his observations of Uranus in the 18th century , which include the following passage : " February 22 , 1789 : A ring was suspected " . Herschel drew a small diagram of the ring and noted that it was " a little inclined to the red " . The Keck Telescope in Hawaii has since confirmed this to be the case , at least for the ? ring . Herschel 's notes were published in a Royal Society journal in 1797 . However , in the two centuries between 1797 and 1977 the rings are rarely mentioned , if at all . This casts serious doubt on whether Herschel could have seen anything of the sort while hundreds of other astronomers saw nothing . Still , it has been claimed by some that Herschel gave accurate descriptions of the ? ring 's size relative to Uranus , its changes as Uranus travelled around the Sun , and its color .
The definitive discovery of the Uranian Rings was made by astronomers James L. Elliot , Edward W. Dunham , and Jessica Mink on March 10 , 1977 , using the Kuiper Airborne Observatory , and was serendipitous . They planned to use the occultation of the star SAO 158687 by Uranus to study the planet 's atmosphere . However , when their observations were analyzed , they found that the star disappeared briefly from view five times both before and after it was eclipsed by the planet . They deduced that a system of narrow rings was present . The five occultation events they observed were denoted by the Greek letters ? , ? , ? , ? and ? in their papers . These designations have been used as the rings ' names since then . Later they found four additional rings : one between the ? and ? rings and three inside the ? ring . The former was named the ? ring . The latter were dubbed rings

4 , 5 and 6 ? according to the numbering of the occultation events in one paper . Uranus 's ring system was the second to be discovered in the Solar System , after that of Saturn .
The rings were directly imaged when the Voyager 2 spacecraft flew through the Uranian system in 1986 . Two more faint rings were revealed , bringing the total to eleven . The Hubble Space Telescope detected an additional pair of previously unseen rings in 2003 ? 2005 , bringing the total number known to 13 . The discovery of these outer rings doubled the known radius of the ring system . Hubble also imaged two small satellites for the first time , one of which , Mab , shares its orbit with the outermost newly discovered ring .

= = General properties = =

As currently understood , the ring system of Uranus comprises thirteen distinct rings . In order of increasing distance from the planet they are : 1986U2R / ? , 6 , 5 , 4 , ? , ? , ? , ? , ? , ? , ? , ? , ? rings . They can be divided into three groups : nine narrow main rings (6 , 5 , 4 , ? , ? , ? , ? , ? , ?) , two dusty rings (1986U2R / ? , ?) and two outer rings (? , ?) . The rings of Uranus consist mainly of macroscopic particles and little dust , although dust is known to be present in 1986U2R / ? , ? , ? , ? , ? and ? rings . In addition to these well @-@ known rings , there may be numerous optically thin dust bands and faint rings between them . These faint rings and dust bands may exist only temporarily or consist of a number of separate arcs , which are sometimes detected during occultations . Some of them became visible during a series of ring plane @-@ crossing events in 2007 . A number of dust bands between the rings were observed in forward @-@ scattering geometry by Voyager 2 . All rings of Uranus show azimuthal brightness variations .
The rings are made of an extremely dark material . The geometric albedo of the ring particles does not exceed 5 ? 6 % , while the Bond albedo is even lower ? about 2 % . The rings particles demonstrate a steep opposition surge ? an increase of the albedo when the phase angle is close to zero . This means that their albedo is much lower when they are observed slightly off the opposition . The rings are slightly red in the ultraviolet and visible parts of the spectrum and grey in near @-@ infrared . They exhibit no identifiable spectral features . The chemical composition of the ring particles is not known . However , they cannot be made of pure water ice like the rings of Saturn because they are too dark , darker than the inner moons of Uranus . This indicates that they are probably composed of a mixture of the ice and a dark material . The nature of this material is not clear , but it may be organic compounds considerably darkened by the charged particle irradiation from the Uranian magnetosphere . The rings ' particles may consist of a heavily processed material which was initially similar to that of the inner moons .
As a whole , the ring system of Uranus is unlike either the faint dusty rings of Jupiter or the broad and complex rings of Saturn , some of which are composed of very bright material ? water ice . However , there are similarities with some parts of the latter ring system ; the Saturnian F ring and the ? ring are both narrow , relatively dark and are shepherded by a pair of moons . The newly discovered outer rings of Uranus are similar to the outer G and E rings of Saturn . Narrow ringlets existing in the broad Saturnian rings also resemble the narrow rings of Uranus . In addition , dust bands observed between the main rings of Uranus may be similar to the rings of Jupiter . In contrast , the Neptunian ring system is quite similar to that of Uranus , although it is less complex , darker and contains more dust ; the Neptunian rings are also positioned further from the planet .

= = Narrow main rings = =

= = = ? ring = = =

The ? ring is the brightest and densest part of the Uranian ring system , and is responsible for about two @-@ thirds of the light reflected by the rings . While it is the most eccentric of the Uranian rings , it has negligible orbital inclination . The ring 's eccentricity causes its brightness to vary over the course of its orbit . The radially integrated brightness of the ? ring is highest near apoapsis and lowest near periapsis . The maximum / minimum brightness ratio is about 2 @.@ 5 ? 3 @.@ 0 . These variations are connected with the variations of the ring width , which is 19 @.@ 7 km at the periapsis and 96 @.@ 4 km at the apoapsis . As the ring becomes wider , the amount of shadowing between particles decreases and more of them come into view , leading to higher integrated brightness . The width variations were measured directly from Voyager 2 images , as the ? ring was one of only two rings resolved by Voyager ? s cameras . Such behavior indicates that the ring is not optically thin . Indeed , occultation observations conducted from the ground and the spacecraft showed that its normal optical depth varies between 0 @.@ 5 and 2 @.@ 5 , being highest near the periapsis . The equivalent depth of the ? ring is around 47 km and is invariant around the orbit .

The geometric thickness of the ? ring is not precisely known , although the ring is certainly very thin ? by some estimates as thin as 150 m . Despite such infinitesimal thickness , it consists of several layers of particles . The ? ring is a rather crowded place with a filling factor near the apoapsis estimated by different sources at from 0 @.@ 008 to 0 @.@ 06 . The mean size of the ring particles is 0 @.@ 2 ? 20 @.@ 0 m , and the mean separation is around 4 @.@ 5 times their radius . The ring is almost devoid of dust , possibly due to the aerodynamic drag from Uranus 's extended atmospheric corona . Due to its razor @-@ thin nature the ? ring disappears when viewed edge @-@ on . This happened in 2007 when a ring plane @-@ crossing was observed .

The Voyager 2 spacecraft observed a strange signal from the ? ring during the radio occultation experiment . The signal looked like a strong enhancement of the forward @-@ scattering at the wavelength 3 @.@ 6 cm near ring ? s apoapsis . Such strong scattering requires the existence of a coherent structure . That the ? ring does have such a fine structure has been confirmed by many occultation observations . The ? ring seems to consist of a number of narrow and optically dense ringlets , some of which may have incomplete arcs .

The ? ring is known to have interior and exterior shepherd moons ? Cordelia and Ophelia , respectively . The inner edge of the ring is in 24 : 25 resonance with Cordelia , and the outer edge is in 14 : 13 resonance with Ophelia . The masses of the moons need to be at least three times the mass of the ring to confine it effectively . The mass of the ? ring is estimated to be about 1016 kg .

= = = ? ring = = =

The ? ring is circular and slightly inclined . It shows significant unexplained azimuthal variations in normal optical depth and width . One possible explanation is that the ring has an azimuthal wave @-@ like structure , excited by a small moonlet just inside it . The sharp outer edge of the ? ring is in 23 : 22 resonance with Cordelia . The ? ring consists of two components : a narrow optically dense component and a broad inward shoulder with low optical depth . The width of the narrow component is 4 @.@ 1 ? 6 @.@ 1 km and the equivalent depth is about 2 @.@ 2 km , which corresponds to a normal optical depth of about 0 @.@ 3 ? 0 @.@ 6 . The ring 's broad component is about 10 ? 12 km wide and its equivalent depth is close to 0 @.@ 3 km , indicating a low normal optical depth of 3 × 10 ? 2 . This is known only from occultation data because Voyager 2 's imaging experiment failed to resolve the ? ring . When observed in forward @-@ scattering geometry by Voyager 2 , the ? ring appeared relatively bright , which is compatible with the presence of dust in its broad component . The broad component is geometrically thicker than the narrow component . This is supported by the observations of a ring plane @-@ crossing event in 2007 , when the ? ring remained visible , which is consistent with the behavior of a simultaneously geometrically thick and optically thin ring .

= = = ? ring = = =

The ? ring is narrow , optically dense and slightly eccentric . Its orbital inclination is almost zero . The width of the ring varies in the range 3 @.@ 6 ? 4 @.@ 7 km , although equivalent optical depth is constant at 3 @.@ 3 km . The normal optical depth of the ? ring is 0 @.@ 7 ? 0 @.@ 9 . During a ring plane @-@ crossing event in 2007 the ? ring disappeared , which means it is geometrically thin like the ? ring and devoid of dust . The width and normal optical depth of the ? ring show significant azimuthal variations . The mechanism of confinement of such a narrow ring is not known , but it has been noticed that the sharp inner edge of the ? ring is in a 6 : 5 resonance with Ophelia .

= = = ? ring = = =

The ? ring has zero orbital eccentricity and inclination . Like the ? ring , it consists of two components : a narrow optically dense component and a broad outward shoulder with low optical depth . The width of the narrow component is 1 @.@ 9 ? 2 @.@ 7 km and the equivalent depth is about 0 @.@ 42 km , which corresponds to the normal optical depth of about 0 @.@ 16 ? 0 @.@ 25 . The broad component is about 40 km wide and its equivalent depth is close to 0 @.@ 85 km , indicating a low normal optical depth of 2 × 10 ? 2 . It was resolved in Voyager 2 images . In forward @-@ scattered light , the ? ring looked bright , which indicated the presence of a considerable amount of dust in this ring , probably in the broad component . The broad component is much thicker (geometrically) than the narrow one . This conclusion is supported by the observations of a ring plane @-@ crossing event in 2007 , when the ? ring demonstrated increased brightness , becoming the second brightest feature in the ring system . This is consistent with the behavior of a geometrically thick but simultaneously optically thin ring . Like the majority of other rings , the ? ring shows significant azimuthal variations in the normal optical depth and width . The narrow component even vanishes in some places .

= = = ? and ? rings = = =

After the ? ring , the ? and ? rings are the brightest of Uranus 's rings . Like the ? ring , they exhibit regular variations in brightness and width . They are brightest and widest 30 ° from the apoapsis and dimmest and narrowest 30 ° from the periapsis . The ? and ? rings have sizable orbital eccentricity and non @-@ negligible inclination . The widths of these rings are 4 @.@ 8 ? 10 km and 6 @.@ 1 ? 11 @.@ 4 km , respectively . The equivalent optical depths are 3 @.@ 29 km and 2 @.@ 14 km , resulting in normal optical depths of 0 @.@ 3 ? 0 @.@ 7 and 0 @.@ 2 ? 0 @.@ 35 , respectively . During a ring plane @-@ crossing event in 2007 the rings disappeared , which means they are geometrically thin like the ? ring and devoid of dust . However , the same event revealed a thick and optically thin dust band just outside the ? ring , which was also observed earlier by Voyager 2 . The masses of the ? and ? rings are estimated to be about 5 × 1015 kg (each) ? half the mass of the ? ring .

= = = Rings 6 , 5 and 4 = = =

Rings 6 , 5 and 4 are the innermost and dimmest of Uranus 's narrow rings . They are the most inclined rings , and their orbital eccentricities are the largest excluding the ? ring . In fact , their inclinations (0 @.@ 06 ° , 0 @.@ 05 ° and 0 @.@ 03 °) were large enough for Voyager 2 to observe their elevations above the Uranian equatorial plane , which were 24 ? 46 km . Rings 6 , 5 and 4 are also the narrowest rings of Uranus , measuring 1 @.@ 6 ? 2 @.@ 2 km , 1 @.@ 9 ? 4 @.@ 9 km and 2 @.@ 4 ? 4 @.@ 4 km wide , respectively . Their equivalent depths are 0 @.@ 41 km , 0 @.@ 91 and 0 @.@ 71 km resulting in normal optical depth 0 @.@ 18 ? 0 @.@ 25 , 0 @.@ 18 ? 0 @.@ 48 and 0 @.@ 16 ? 0 @.@ 3 . They were not visible during a ring plane @-@ crossing event in 2007 due to their narrowness and lack of dust .

= = Dusty rings = =

= = = ? ring = = =

The ? ring was one of two rings discovered by Voyager 2 in 1986 . It is a narrow , faint ring located just inside the ? ring , between it and the shepherd moon Cordelia . This moon clears a dark lane just inside the ? ring . When viewed in back @-@ scattered light , the ? ring is extremely narrow ? about 1 ? 2 km ? and has the equivalent optical depth 0 @.@ 1 ? 0 @.@ 2 km at the wavelength 2 @.@ 2 ?m . The normal optical depth is 0 @.@ 1 ? 0 @.@ 2 . The optical depth of the ? ring shows strong wavelength dependence , which is atypical for the Uranian ring system . The equivalent depth is as high as 0 @.@ 36 km in the ultraviolet part of the spectrum , which explains why ? ring was initially detected only in UV stellar occultations by Voyager 2 . The detection during a stellar occultation at the wavelength 2 @.@ 2 ?m was only announced in 1996 .

The appearance of the ? ring changed dramatically when it was observed in forward @-@ scattered light in 1986 . In this geometry the ring became the brightest feature of the Uranian ring system , outshining the ? ring . This observation , together with the wavelength dependence of the optical depth , indicates that the ? ring contains significant amount of micrometer @-@ sized dust . The normal optical depth of this dust is 10 ? 4 ? 10 ? 3 . Observations in 2007 by the Keck telescope during the ring plane @-@ crossing event confirmed this conclusion , because the ? ring became one of the brightest features in the Uranian ring system .

Detailed analysis of the Voyager 2 images revealed azimuthal variations in the brightness of the ? ring . The variations appear to be periodic , resembling a standing wave . The origin of this fine structure in the ? ring remains a mystery .

= = = 1986U2R / ? ring = = =

In 1986 Voyager 2 detected a broad and faint sheet of material inward of ring 6 . This ring was given the temporary designation 1986U2R . It had a normal optical depth of 10 ? 3 or less and was extremely faint . It was visible only in a single Voyager 2 image . The ring was located between 37 @,@ 000 and 39 @,@ 500 km from the centre of Uranus , or only about 12 @,@ 000 km above the clouds . It was not observed again until 2003 ? 2004 , when the Keck telescope found a broad and faint sheet of material just inside ring 6 . This ring was dubbed the ? ring . However the position of the recovered ? ring differs significantly from that observed in 1986 . Now it is situated between 37 @,@ 850 and 41 @,@ 350 km from the centre of the planet . There is an inward gradually fading extension reaching to at least 32 @,@ 600 km , or possibly even to 27 @,@ 000 km ? to the atmosphere of Uranus .

The ? ring was observed again during the ring plane @-@ crossing event in 2007 when it became the brightest feature of the ring system , outshining all other rings combined . The equivalent optical depth of this ring is near 1 km (0 @.@ 6 km for the inward extension) , while the normal optical depth is again less than 10 ? 3 . Rather different appearances of the 1986U2R and ? rings may be caused by different viewing geometries : back @-@ scattering geometry in 2003 ? 2007 and side @-@ scattering geometry in 1986 . However , changes during the past 20 years in the distribution of dust , which is thought to predominate in the ring , cannot be ruled out .

= = = Other dust bands = = =

In addition to the 1986U2R / ? and ? rings , there are other extremely faint dust bands in the Uranian ring system . They are invisible during occultations because they have negligible optical depth , though they are bright in forward @-@ scattered light . Voyager 2 's images of forward @-@ scattered light revealed the existence of bright dust bands between the ? and ? rings , between the ? and ? rings , and between the ? ring and ring 4 . Many of these bands were detected again in 2003 ? 2004 by the Keck Telescope and during the 2007 ring @-@ plane crossing event in backscattered light , but their precise locations and relative brightnesses were different from during the Voyager observations . The normal optical depth of the dust bands is about 10 ? 5 or less . The dust particle size distribution is thought to obey a power law with the index p = 2 @.@ 5 ± 0 @.@ 5 .

In addition to separate dust bands the system of Uranian rings appears to be immersed into wide and faint sheet of dust with the normal optical depth not exceeding 10 ? 3 .

Outer ring system

In 2003 ? 2005 , the Hubble Space Telescope detected a pair of previously unknown rings , now called the outer ring system , which brought the number of known Uranian rings to 13 . These rings were subsequently named the ? and ? rings . The ? ring is the outermost of the pair , and is twice the distance from the planet as the bright ? ring . The outer rings differ from the inner narrow rings in a number of respects . They are broad , 17 @,@ 000 and 3 @,@ 800 km wide , respectively , and very faint . Their peak normal optical depths are 8 @.@ 5 × 10 ? 6 and 5 @.@ 4 × 10 ? 6 , respectively . The resulting equivalent optical depths are 0 @.@ 14 km and 0 @.@ 012 km . The rings have triangular radial brightness profiles .

The peak brightness of the ? ring lies almost exactly on the orbit of the small Uranian moon Mab , which is probably the source of the ring ? s particles . The ? ring is positioned between Portia and Rosalind and does not contain any moons inside it . A reanalysis of the Voyager 2 images of forward @-@ scattered light clearly reveals the ? and ? rings . In this geometry the rings are much brighter , which indicates that they contain much micrometer @-@ sized dust . The outer rings of Uranus may be similar to the G and E rings of Saturn as E ring is extremely broad and receives dust from Enceladus .

The ? ring may consist entirely of dust , without any large particles at all . This hypothesis is supported by observations performed by the Keck telescope , which failed to detect the ? ring in the near infrared at 2 @.@ 2 ?m , but detected the ? ring . This failure means that the ? ring is blue in color , which in turn indicates that very small (submicrometer) dust predominates within it . The dust may be made of water ice . In contrast , the ? ring is slightly red in color .

Dynamics and origin

An outstanding problem concerning the physics governing the narrow Uranian rings is their confinement . Without some mechanism to hold their particles together , the rings would quickly spread out radially . The lifetime of the Uranian rings without such a mechanism cannot be more than 1 million years . The most widely cited model for such confinement , proposed initially by Goldreich and Tremaine , is that a pair of nearby moons , outer and inner shepherds , interact gravitationally with a ring and act like sinks and donors , respectively , for excessive and insufficient angular momentum (or equivalently , energy) . The shepherds thus keep ring particles in place , but gradually move away from the ring themselves . To be effective , the masses of the shepherds should exceed the mass of the ring by at least a factor of two to three . This mechanism is known to be at work in the case of the ? ring , where Cordelia and Ophelia serve as shepherds . Cordelia is also the outer shepherd of the ? ring , and Ophelia is the outer shepherd of the ? ring . However no moon larger than 10 km is known in the vicinity of other rings . The current distance of Cordelia and Ophelia from the ? ring can be used to estimate the ring ? s age . The calculations show that the ? ring cannot be older than 600 million years .

Since the rings of Uranus appear to be young , they must be continuously renewed by the collisional fragmentation of larger bodies . The estimates show that the lifetime against collisional disruption of a moon with the size like that of Puck is a few billion years . The lifetime of a smaller satellite is much shorter . Therefore , all current inner moons and rings can be products of disruption of several Puck @-@ sized satellites during the last four and half billion years . Every such disruption would have started a collisional cascade that quickly ground almost all large bodies into much smaller particles , including dust . Eventually the majority of mass was lost , and particles survived only in positions that were stabilized by mutual resonances and shepherding . The end product of such a disruptive evolution would be a system of narrow rings . However , a few moonlets must still be embedded within the rings at present . The maximum size of such moonlets is probably around 10 km .

The origin of the dust bands is less problematic . The dust has a very short lifetime , 100 ? 1000 years , and should be continuously replenished by collisions between larger ring particles , moonlets and meteoroids from outside the Uranian system . The belts of the parent moonlets and particles are themselves invisible due to their low optical depth , while the dust reveals itself in forward @-@ scattered light . The narrow main rings and the moonlet belts that create dust bands are expected to differ in particle size distribution . The main rings have more centimeter to meter @-@ sized bodies . Such a distribution increases the surface area of the material in the rings , leading to high optical density in back @-@ scattered light . In contrast , the dust bands have relatively few large particles , which results in low optical depth .

= = Exploration = =

The rings were thoroughly investigated during the Voyager 2 spacecraft 's flyby of Uranus in January 1986 . Two new faint rings ? ? and 1986U2R ? were discovered bringing the total number then known to eleven . Rings were studied by analysing results of radio , ultraviolet and optical occultations . Voyager 2 observed the rings in different geometries relative to the sun , producing images with back @-@ scattered , forward @-@ scattered and side @-@ scattered light . Analysis of these images allowed derivation of the complete phase function , geometrical and Bond albedo of ring particles . Two rings ? ? and ? ? were resolved in the images revealing a complicated fine structure . Analysis of Voyager 's images also led to discovery of 10 inner moons of Uranus , including the two shepherd moons of the ? ring ? Cordelia and Ophelia .

= = List of properties = =

This table summarizes the properties of the planetary ring system of Uranus .