NOVA

Resolution on Saturn

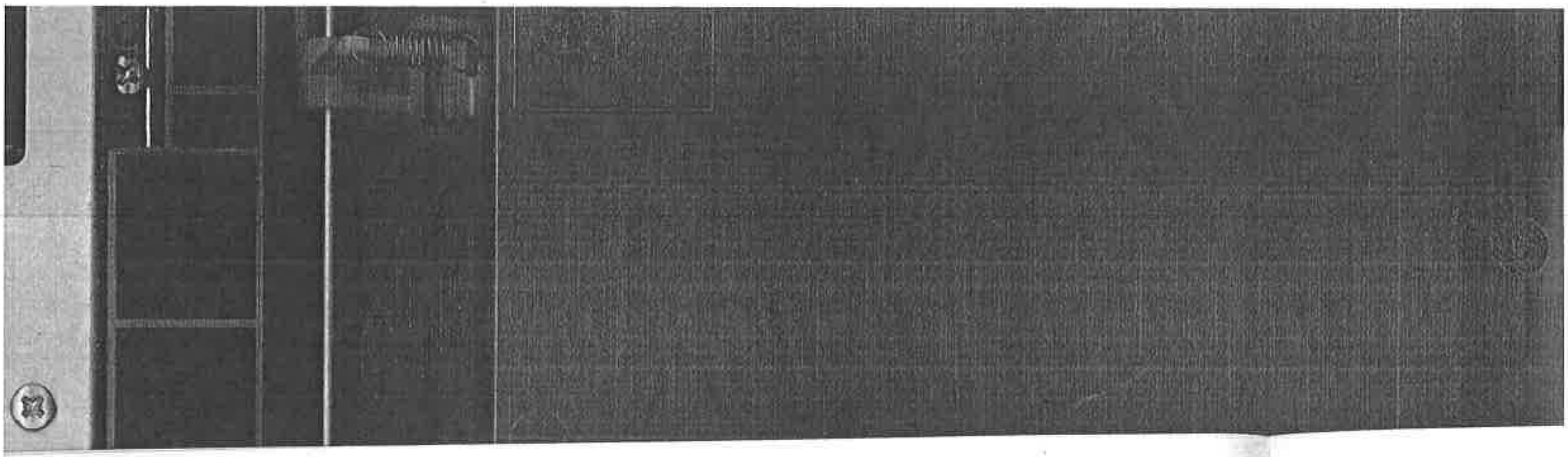
NOVA # 810

This program was originally broadcast on PBS on August 25, 1981.

Major funding for NOVA is provided by this station and other public television stations. Additional funding is provided by grants from TRW, Inc., and the National Science Foundation.

Resolution on Saturn

WGBH Transcripts
125 Western Avenue
Boston, Massachusetts 02134
(617) 492-2777



This mos
Voyager
miles of

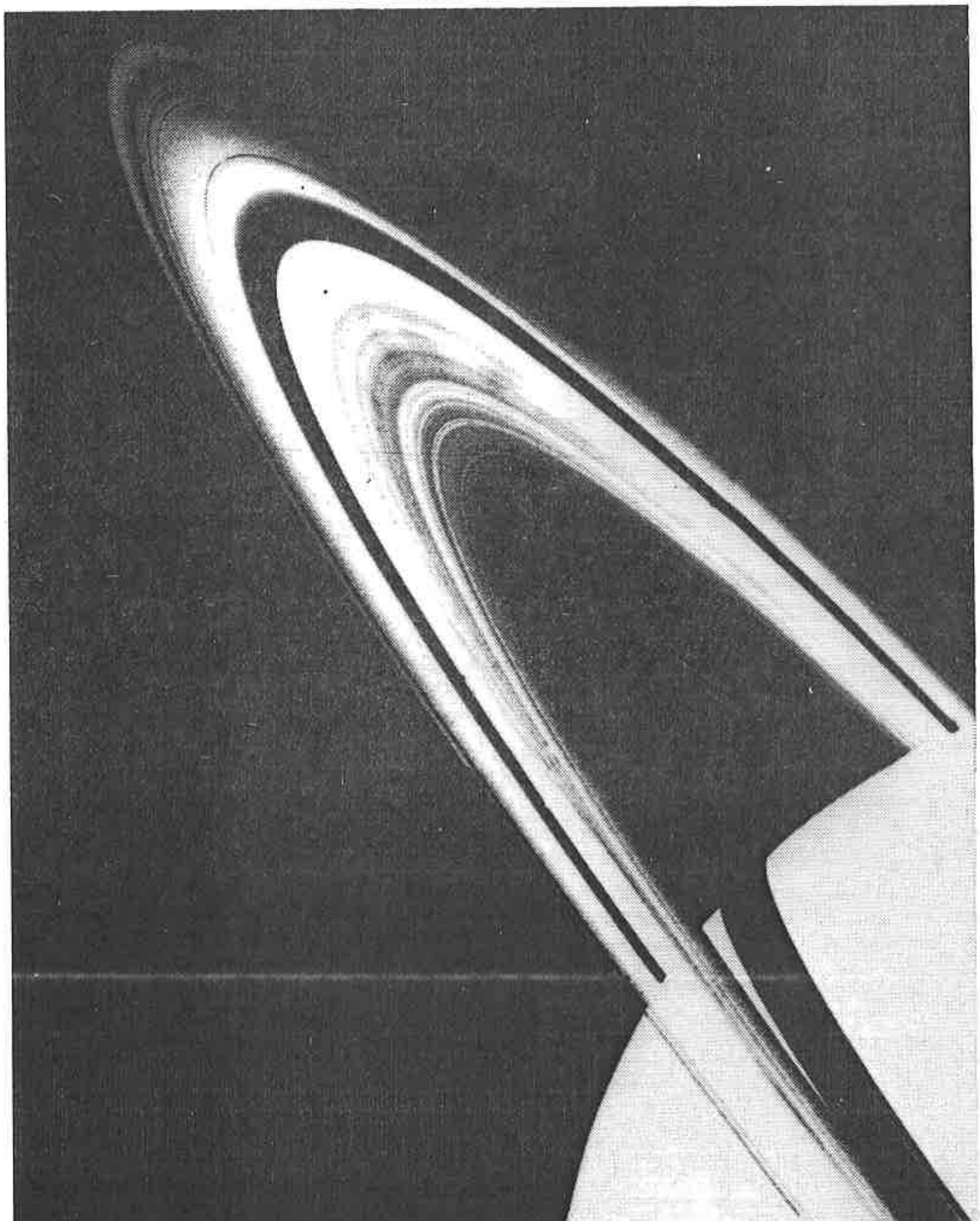


Photo courtesy of Jet Propulsion Laboratory

This mosaic of Saturn's rings was compiled from photographs taken by NASA's Voyager I on November 12, 1980, when the spacecraft came within 77,174 miles of the planet.

NARRATOR
In the fall of 1977, NASA launched the two unmanned Voyager spacecraft. Sitting on rockets 162 feet tall, the fragile robot spacecraft were starting on a journey of billions of miles, a mission that was to take over twelve years to complete. For the Voyager spacecraft were designed to explore the outer solar system.

Of the two identical spacecraft launched within a month of each other, Voyager I was to go ahead and arrive first at Jupiter and then Saturn. Its journey to Saturn, nearly a thousand million miles away, was to take over three years. Voyager I was designed to take a first close look at worlds that had never been seen in detail before.

This extraordinary film, shot through the Mount Wilson telescope in California more than 25 years ago, shows Jupiter's inner moon, Io, orbiting the giant planet. The shadow of the moon on the planet can be clearly seen. All the giant planets of the outer solar system are made not of rock, but of gas. Jupiter and its twin, Saturn, are miniature solar systems in their own right, fully equipped with whole collections of moons. These worlds are so far away that new and powerful equipment had to be built to communicate with the robot spacecraft travelling to them.

A giant antenna was built at Goldstone in California's Mojave Desert. This dish was designed to pick up a signal no stronger than a refrigerator light bulb, over four thousand million miles away. A similar dish near Madrid, in Spain, and one near Canberra, Australia ensure contact with a spacecraft even as the Earth rotates. This was only one small part of the gigantic planning effort that went into the Voyager mission.

Eighteen months out and Voyager I encountered Jupiter. Approaching close to the giant planet and its inner moon, Io, the spacecraft trajectory bent through more than a right angle. The encounter was designed to boost Voyager's speed to 35,000 miles an hour...on to Saturn, slowing Jupiter itself in its orbit by about one foot per trillion years.

Travelling ten times faster than a rifle bullet, Voyager shot this actual movie of Jupiter and the four large moons orbiting around it. Of these moons, Io is the most remarkable. It is covered in volcanic sulphur and is now thought to generate more than a million megawatts of electrical energy from edge to edge. Besides Io, Voyager I's major mission targets were to be encountered more than a year later -- at Saturn.

This computer animation shows Voyager I's trajectory at Saturn. The spacecraft was targeted to pass 2400 miles over the top of the giant moon Titan's atmosphere. Titan, orbiting Saturn once every 16 days, was encountered first, so that there was time to relay all the data back to Earth before the next major mission objective.

For about to loop below, around and then up behind Saturn, the spacecraft is targeted for a very special trajectory which will allow it to shine its radio beam back to Earth through all the rings of Saturn in turn. By

NARRATOR (Continued)
listening to the interference, the Voyager team was planning to solve one of Saturn's greatest mysteries: the exact composition of the majestic rings that girdle the planet.

This view shows the spacecraft looking back at Saturn, the Earth and the sun in the distance. The Earth, seen by Voyager, is first eclipsed by Saturn and then emerges in the small gap between Saturn and the rings, just here.

By shining the spacecraft radio beam back to Earth and listening to the interference as the beam passes through each part of the rings in turn, the team planned to find out the exact sizes of the millions of tiny moonlets that are known to make up the rings. But in <u>doing</u> this, the spacecraft itself was sacrificed.

All of Saturn's moons and its rings orbit in roughly the same plane around the planet. In fact the Saturnian system closely resembles the solar system where all the planets orbit around the sun in the same plane, called the *ecliptic*. In hooking up behind Saturn to shine its radio beam through the rings, Voyager I's future was sacrificed, for its trajectory left the ecliptic plane. The spacecraft cannot encounter any more planets. It heads upwards and outwards into interstellar space.

NASA shares its triumphs by making full-scale computer animations that show the precise trajectory of the spacecraft. This is what the Voyager team expected to find at Saturn. It is a compilation of all the best guesses.

The small inner moons of Saturn were targeted for photographs. They are thought to have a controlling influence on the myriads of tiny moonlets that make up the rings.

At Mission Control in Los Angeles, the scientific team waited for the real pictures of Saturn and its rings. The spacecraft, nearly a thousand million miles away, successfully transmitted back to Earth over 17,000 pictures. Each black and white image is made of 64,000 dots or *pixels*. Each pixel has 256 digital levels of gray. So by using sophisticated computer programs, pictures that at first sight seem featureless can be enhanced or developed by mathematical processing. In this way, features partially hidden under clouds of haze or dust can be revealed in all their detail.

By manipulating color filters in front of the spacecraft cameras and shooting the same scene three times, the imaging team can assemble a color picture from three black and white images shot through red, green and blue filters. By sequencing such pictures together, the spacecraft can even shoot color movies. And this is what Voyager actually saw as it approached Saturn.

Close in, wrapped in a soft blanket of haze, Saturn is incredibly beautiful. The sheer size of Saturn is difficult for beings from Earth to comprehend, for Saturn is truly gigantic. More than 650 Earths would fit into the volume of the planet. But Saturn, unlike Earth, is made not from rock, but from gas.

NARRATOR (Continued)
As this computer-enhanced image shows, Saturn is distinctly oval. The planet is flattened by the speed with which it spins. A Saturnian day is only ten hours long. Underneath a turbulent atmosphere is an immensely deep ocean of liquid hydrogen. Deep down it is so compressed that it behaves like a liquid metal. And at the very center is a rocky core -- a solid planet rather larger than the Earth, but enveloped in an ocean of liquid gas more than thirty thousand miles deep.

Saturn's atmosphere is blanketed in a thick layer of smog. The first problem the team needed to solve was how to construct the complicated computer programs that would reveal the detail underneath. They succeeded and, computer-enhanced, a previously unseen Saturn emerged from underneath the haze. The atmosphere is a turbulent place. It is patterned with spots and vortices trailing for tens of thousands of miles.

These are the tops of storm clouds racing across the Saturnian sky. The equatorial winds blow at up to one thousand miles per hour.

Girdling the planet are the rings, 38,000 miles across.

The names for Saturn's rings were worked out long before any spacecraft got there. They are based on the two most noticeable divisions in the rings: the Cassini divisions and the boundary with the inner diffuse crepe ring. So in the interest of simplicity, the rings were called A, B, and C for crepe ring. But as the resolution has improved on the rings, the naming has had to be extended and has become absurdly complicated.

Everything inside the C ring is the D ring. The very diffuse material outside the A ring that is invisible from Earth is the E or extended ring. while the very small thin ring outside the A ring, but inside the E ring, became the F ring. But even this complicated scheme underestimates the sheer complexity of Saturn's rings.

This actual Voyager image has been computer-enhanced to reveal all the detail in the rings. The structure is enormously complicated. The rings are so full of detail that they have been compared to a gigantic phonograph record. Composed of billions of small independently orbiting chunks of ice, the entire ring system is almost forty thousand miles across and, surprisingly, less than a mile thick.

Formed with Saturn more than four thousand million years ago, the rings are a window into that ancient time when the solar system was born. Over eons, some process seems to have steadily marshalled the myriad swarms of billions upon billions of boulders of ice into the structure the rings now have.

Close as Voyager flew to the rings, it was not close enough for the spacecraft cameras to pick out the individual boulders of the rings to find out how big they are. But by catching the Earth in the gap between the rings and the planet and then transmitting the spacecraft radio beam back to Earth through the rings and listening to the interference, the spacecraft was programmed to find that out.

VON ESHLEMAN
Now I can illustrate the concept of the radio waves from the spacecraft going back towards the Earth by means of a laser light in my hand. Now, I will show how the intersection of the radio path and the ring plane draws out a path through the rings allowing measurements to be made of the characteristics of the particles...where the radio waves are sensitive to particles that are equal to what we call its *radio wave length*, which is just this long...and larger particles.

We can illustrate the way that the radio beams pass through the rings of Saturn and give us information back on Earth about the characteristics of the particles by this illustration of this laser light shining through various types of cloth. In this case, we're illustrating the effect of relatively large particles where the scattered energy going on towards the Earth is concentrated in several quite bright beams. If the particles are smaller in size and more randomly distributed, we get an effect of this type on the Earth.

We can study that pattern to tell us more about the particles, their characteristics and their sizes. If the particles are very small, it's more like the light passing through this wax paper, where we have a more uniform spread of the energy. For example, we found that the particles in the C ring are on the average about a meter in diameter, quite large particles in comparison with the pebble size that some people had thought might be present in those rings. Of course there are larger particles and smaller particles, but the average size is in the order of a meter.

NARRATOR
The particles in the outer or A ring are on average thirty feet across. Some are as large as office blocks. In the central or B ring, the ring boulders are jostling so close together that, on first analysis of the results, the spacecraft radio beam appears not even to have penetrated through. In the inner or C ring, the particles are, on average, about the size of automobiles.

As this simulation shows, the boulders of the rings, now thought to be largely made of ice, orbit around Saturn at different speeds, depending on how far away they are from the planet. Ring boulders closer to Saturn orbit around faster than ring boulders farther away. This property of the rings led the Voyager team to expect, long before the spacecraft got to Saturn, that all the features in the rings would be exactly circular -- any non-circular feature would be quickly destoyed by this inexorable bending out of shape.

But as Voyager approached Saturn, the team became aware of curious irregularities in the central or B ring. The ring appears to have spokes. Dark line radiating out from the planet and patterning the ring material. The baffled imaging team decided to make a movie from the Voyager images.

This is the movie, shot as the spacecraft approached Saturn with the sun at its back.

NARRATOR (Continued)
The spokes which can be seen moving in the middle of the rings appear as dark lines revolving around. The spacecraft was reprogrammed to shoot another movie as it left Saturn and was facing the sun.

From this view the spokes, which can be seen emerging from the shadow, not only appear very unspoke-like and irregular, but they have changed color. Now seen from the other side of Saturn, they are not black, but white.

This was the vital clue as to what the spokes actually are, for the property of changing brightness with the direction of the light is shown only by minute objects, like specks of dust caught in a sunbeam. The spokes are probably made of clouds of tiny particles, possibly dust or a frost of ice, levitated above the boulders of the rings. How these clouds of tiny particles are formed is still an unsolved mystery.

It was expected that the orbits of all the ring particles would be exactly circular. But by matching two pictures taken of opposite sides of the rings, the team discovered a non-circular or eccentric ring. On the other hand, it is perfectly possible that this is the only really circular ring and that all the rest of the rings are eccentric. There is no way of telling from this evidence.

The structure of the rings was found to be very complicated. Before Voyager, the Cassini division was thought to be empty. But even the Cassini division contains whole rings of its own, regularly spaced.

For this is the central mystery posed by Saturn's rings. What is it that has marshalled the independently orbiting boulders of the rings into the complicated structures seen by the Voyager cameras? Could it be that it is the gravitational influence of Saturn's moons, orbiting far outside the rings, that has, over billions of years, displaced the swarms of icy boulders and given the rings their unique structure?

JEFFREY CUZZI
Now of course as we know, all this ring material, this is all independent. Particles in independent orbits are all little moons that are meters or so in size, or smaller. If a particle finds itself in an orbital location that's a simple fraction ratio of a moon's period -- in other words, if the particle goes around, let's say twice for every single time that the moon goes around -- over time the particle always sees the moon in this same location every time it comes around to its location; the moon is right back there.

So over time, the orbit of the particle gets stretched out, you might say... made more eccentric. It collides with the particles that are further from the resonance location and it's removed from that orbit. So orbits that are in or near a resonance with a moon -- and there are, as you know, 15 moons; so there are lots of possibilities for resonances -- become unstable. The outer edge of the A ring, the Cassini and the inner edge of the B ring have long been known to be major resonances with Mimas, which is Saturn's innermost major classical satellite.

NARRATOR
This is the resonance theory that the gravitational influence of Saturn's moons can clear spaces in the rings. If a ring boulder -- shown here as a point of light -- orbits Saturn at precisely twice the rate of a moon, every second orbit the boulder will be bumped out slightly by the gravity of the moon. The effect of this happening over and over again over eons of time is to pull the ring boulder into a different orbit from its neighbors.

This elliptical orbit causes it to collide with nearby boulders, clearing a gap in the rings by slowing them all into different orbits. Long before the spacecraft ever got to Saturn, the resonance theory had predicted exactly where all the divisions in the rings would be found. Over billions of years, the gravitational harmonies set up by Saturn's moons were fully expected to have marshalled the vast populations of boulders that compose the rings into precisely spaced divisions.

The only problem with this resonance theory which so elegantly links the rings with the moons in a kind of divine harmony of the spheres, is that it turned out to be wrong.

The actual divisions in Saturn's rings were found by the Voyager I spacecraft in different locations from where the resonance theory had so confidently placed them.

But if resonances with Saturn's moons are not responsible, what is the reason for all the divisions in the rings? A different mechanism must be involved. A clue to what that might be was photographed by Voyager I at the very edge of the rings. Just where a resonance should have been there was a moon...a moon that had never been seen before.

BRAD SMITH
Now here we see a small rather insignificant satellite roughly a hundred kilometers across. But its importance lies in its location. It is orbiting just outside the bright ring system of Saturn. And ever since the nature of the ring system has been understood -- that is, the rings represent swarms of billions upon billions of tiny particles -- there has been the question of what constrains them, what keeps them from drifting off into space? And now we have the answer to that: it's this little insignificant tiny body orbiting just outside the bright ring system. Its own gravitational interaction keeps those particles in place, kept the rings there for billions of years.

NARRATOR
The gravitational effect of a moon only the size of Kansas City, orbiting outside the main ring system, keeps the rings in place. Outside the A ring is the F ring. Why is this ring so thin? Voyager I also discovered another two moons orbiting just inside and outside this F ring. The inner moon, S14, orbits Saturn slightly faster than the boulders of the F ring and as this animation shows, as it passes, it slows the boulders and pushes them into an outer orbit, confining the inner edge of the ring. Outside the F

NARRATOR (Continued)
ring, the moon S13 orbits slower. As the F ring passes S13, the gravity of the small moon presses the ring in on the outer edge. S13 and 14 behave like shepherds, fencing the F ring into a narrow line. The activities of the two shepherding moons might explain why the F ring has a curious braided structure, almost as if it is constructed of entirely separate strands.

But the real implication of this unexpected discovery is this: is the structure of Saturn's rings controlled by small shepherd moons that Voyager's camera couldn't see embedded among the boulders of the rings? And if so, what is the function of the resonances? Strangely, Voyager discovered not divisions, but <u>concentrations</u> of material at the resonance locations.

Seen now from the other side of Saturn, looking back at the sun, thicker parts of the rings appear dark, not bright, because the sunlight cannot penetrate. The resonance theory, so bad at predicting where gaps are in the rings, seems to predict where these concentrations of material are. Saturn's moons appear to be slowly collecting the boulders of the rings together at the regularly spaced resonance locations. This unexpected discovery opens a window into the most distant past. Could this be a fossil of how the Earth and planets formed when the solar system began?

JEFFREY CUZZI
Current theory holds that the solar system...as you know, all the planets are in the same plane...that is that the solar system disc -- with the sun in the middle, there was probably a disc, a pancake-shaped object of dust and gas flowing around, more or less like Saturn's rings do. If say, Jupiter or Saturn (of course they are much bigger) had formed early, they would have had resonances within the disc of the planets and maybe these resonances had something to do with coalescing and collecting the material that would eventually become the planets.

NARRATOR
The sun and planets formed from a huge cloud of gas and dust. About four and a half thousand million years ago, this cloud began to collapse. The sun was to form at the center. The dust and gas that was to become the planets settled into a huge disc of material swirling around the sun much like Saturn's rings. The supposition is that Jupiter and Saturn formed first out of this ring.

Only later did resonances caused by their huge collecting masses determine where the inner planets would form at the resonance locations. This explains why the orbits of the inner planets have a precise mathematical relationship to the orbits of Jupiter and Saturn. Only then did the sun heat up and a hot wind of particles destroyed the remnants of the primeval ring and pushed the debris far out into space, erasing the evidence of the birth of our solar system.

Perhaps we owe our existence to Jupiter and Saturn, for if we on Earth were not almost exactly at our present distance from the sun, life could never have evolved on our planet.

NARRATOR (Continued)
Besides its rings, Saturn has more than 15 moons. The Voyager I trajectory was chosen to pass close to the largest of these moons, Titan, flying twenty-four hundred miles over its visible surface, and then to travel on through the Saturnian system, photographing the many inner moons of Saturn on the way.

Voyager I was to photograph 13 of these moons, including a close encounter with icy Rhea.

This actual Voyager movie shows the moons orbiting around, speeded up a hundred thousand times.

Titan is passing behind Saturn now.

BRADFORD SMITH
This peculiar-looking object here is one of the two so-called co-orbital satellites of Saturn. They're almost in the same orbit. In fact, their orbital radii are only about 50 kilometers apart, and these objects are more like 150 kilometers in diameter. So clearly they are not going to be able to sneak by one another. They are closing in right now and we expect that there'll be some sort of gravitational interaction that prevents them from actually colliding.

NARRATOR
As this animation shows, these two oddly shaped moons, called S10 and S11, move outside the rings in almost exactly the same orbit. But it isn't quite the same, so one, in the inner orbit, is slowly overtaking the other. Every four years they should collide, but it is thought that, as they approach, the influence of each on the other causes them to exchange orbits.

The faster one is slowed into an outer orbit and the slow one speeds up into an inner orbit. Now they move apart from each other. They will meet again in four years' time.

BRADFORD SMITH
But notice the very peculiar shape of this object. That strongly suggests that this is half of a single satellite that was impacted perhaps by a meteorite that split it in two. And these two satellites now, almost in the same orbit, are the two halves of some original satellite once.

NARRATOR
This potato-shaped moon, perhaps originally one-half of a larger satellite, is so small that its own minute gravity is not strong enough to crush its own shape into a sphere.

Before the Voyager I mission, virtually nothing was known about Saturn's many moons. As this telescope photograph shows, most of them were known to astronomers as mere points of light.

NARRATOR (Continued)
The closest large moon to Saturn is Mimas, named after a mythological companion of the god Saturn, but never seen in detail before.

What you are hearing now is the actual radio sound near Mimas recorded by the Voyager I spacecraft. Roughly the size of the state of Iowa, Mimas is apparently mostly made of ice. It is intensely cratered. Huge impacts seem to have cracked this moon in places.

On the other side, Voyager I photographed an enormous impact crater. Staring like a huge eye into space, this gigantic crater gives Mimas a bizarre appearance, like some imaginary planet.

EUGENE SHOEMAKER
I have here five bullets and we're going to pretend that these are comets, and we're going to fire these comets at five rocks up there which you're going to pretend are moons of Saturn. Now actually, these shells only travel at about a kilometer per second and a comet, striking a moon of Saturn, will be traveling at about 10. So the velocities are not quite right. What we're concerned about is the energy that we're putting into the satellite in comparison to the size of the satellite, and for that our experiment is really quite satisfactory.

Alright, now we'll start with the smallest satellite and we'll work up to progressively larger satellites.

Alright, now let's look at the first case -- the rock is gone, completely fragmented and the fragments dispersed at relatively high velocity. In the second rock, which is here, we're just at the threshold of catastrophic disruption. Most of the rock is still here, but pieces are scattered about. If this had been the satellite, the pieces would just barely have separated, and the gravitation of the satellite would have brought them back together.

Now we go to a satellite that's a little bit bigger for the same size crater, and we see that we formed a crater, in fact, and the rock was partly cracked, as we can see here, but pretty much it held together. And then we go to still a bigger object, and the satellite is now intact and what we see is just the crater...and otherwise, the satellite is not damaged.

Now we had a little bit of a trick with this last shot -- this is still a bigger satellite, and we made a crater. As it turns out, there was a flaw in this rock and we knocked a corner, and so it didn't quite fit our model and of course we might expect that the satellites, having been bombarded many, many times by comets, will be full of flaws. However, gravity will hold them together and there was not gravity to keep this piece from flying off.

NARRATOR
An impact from a comet traveling at more than ten kilometers per second was almost enough to shatter Mimas. But not quite. The shock was just below the threshold which, if exceeded, would have broken Mimas into fragments.

NARRATOR (Continued)
Next out, Enceladus.

Voyager I did not take high resolution pictures of this enigmatic moon, for its trajectory carried it too far away. Enceladus is roughly 300 miles in diameter, and is apparently made of slushy ice.

Next out, Tethys.

This strange world is larger than its sisters closer to Saturn, about 650 miles in diameter. Black and white spacecraft images reveal that one side of this moon is marked with what may be a very large impact crater, as Mimas is. On the other side a chasm, more than twice the size of the Grand Canyon, twists across the face of Tethys.

Like its sisters, Tethys is thought to be made of ice. But the ice of Tethys is very cold. Unlike ice at zero degrees centigrade, which is relatively soft, the ice of Tethys, frozen to minus two hundred degrees Centigrade, is extremely brittle. Tethys is cold enough and brittle enough to have been shattered into fragments by comet impact. But it would have survived by recollecting under its own gravity into a fractured ball of icy debris.

But did this ever happen to Tethys? There is evidence that it did, for the huge chasm running across the moon is probably the visible part of a fault running right through the entire volume, a record of the re-collection of Tethys.

Next out, Dione.

Dione is roughly 700 miles across. At first sight, this moon seems similar to Saturn's other icy moons further in -- an intensely cratered ball of ice with cracks running across its surface for hundreds of miles, and evidence of huge impacts.

But it seems that at some point in Dione's checkered history, the surface cracked, and new material escaped from the interior, coloring the surface. For the other side of Dione is painted with strange patterns. Christened wispy terrain, this had never been seen before anywhere else in the solar system. Besides its wispy terrain, Dione exhibits a strange orbital curiosity.

It has a minute companion, Dione B, another satellite of Saturn in exactly the same orbit, but slightly ahead. Dione and Dione B are gravitationally locked together by a technicality of gravitational theory known as Trojan points. Unfortunately, Dione B remained tantalizingly out of range of the cameras of Voyager I.

By the time the spacecraft reached Rhea, it had been accelerated to 45,000 miles an hour by Saturn's gravity boost. The team was worried that the pictures the spacecraft took of Rhea would be smudged by its velocity. So the trajectory engineers used the attitude control rockets to compensate for Voyager's speed by panning the spacecraft camera. The technique worked and the scientists were able to study the surface of Rhea, nearly a thousand miles in diameter.

NARRATOR (Continued)
It was just as well the pictures were sharp, for on close investigation of the craters that mark this moon's icy surface, the geologist attached to the Voyager team found an important clue to the origin of the material out of which Rhea and indeed the entire Saturnian system were formed, over four and a half thousand million years ago.

LAWRENCE SODERBLOM
We find that Rhea is densely cratered, drenched by comparison to Dione. And so it has to have preserved its early bombardment period much, much better. But there are some very interesting patterns we see in this cratering pattern on Rhea. As a matter of fact, it took us a couple of days to see it. All one would see at first is just an assemblage of densely cratered surface. But if you look very carefully, you'll see that, in fact, in this region over here, if you look at this kind of pie-shaped piece on Rhea, there are almost no craters larger than something about...oh, the size of a pea at this scale here. Whereas in this part of the planet, large craters are nearly standing shoulder to shoulder. Something had to happen.

There's no way we could imagine that this piece of Rhea was protected and was lucky enough or unlucky enough not to have received the large craters that formed over here. What had to have happened? Well, the best model is that something came out of Rhea. We call these flows, in the case of terrestrial planets, *vulcanism*. So the vulcanism here is probably some form of slush and mush that flows out in the form of a slurry. But it had to flow out on the surface and blanket all the large craters here. Then cratering had to continue because this area that's been what we call *resurfaced* still has a dense population of craters, but no large ones. Now, how can that be?

In the case of the moon, we find areas that were densely cratered and lightly cratered. Basically, there was cratering and then there was no cratering. But in the case of Rhea, there's a case in which there was a period of cratering in which there were a lot of large things and there was a period of cratering in which there were smaller bodies only. One of the suggestions is that the Saturnian satellites have to live in a system in which they have to not only belong to the solar system at large, with all this swirling stuff going around the sun battering them, but also they have to put up with this sort of Saturnian satelllite system, in which they're going around Saturn with all this junk. And both of those populations of stuff going around Saturn and going around the sun are cratering and bombarding these surfaces.

NARRATOR
So the suggestion is that the surface of Rhea was formed in two separate bombardments. The first bombardment included objects that were large enough to make big craters which evenly peppered the entire surface of the moon.

NARRATOR (Continued)
Then parts of Rhea cracked and some process akin to vulcanism caused new material in the form of slush to be forced out from the inside. This resurfaced a whole area of Rhea. In this place, the original record of cratering was erased.

Then the second phase of bombardment started. This time there were no large bodies to make big craters. The resurfaced area was patterned only with small impact craters.

Now, thousands of millions of years later, Rhea has a record on its surface of each of the two epochs of cratering that formed it.

But the main objective of the entire Voyager I mission was a close encounter with Titan, flying twenty-four hundred miles over its visible surface. This giant moon is a planet in its own right. Titan has an atmosphere known to contain the gas methane, and has clouds. For years, astronomers have hoped that Titan is a moon where alien life may exist.

As Voyager approached Titan, the team was planning to photograph the surface through gaps in the cloud deck. With this in mind, the spacecraft was programmed to cover the entire surface of Titan with high resolution images.

TOBY OWENS
We thought there was a chance that we'd see the surface on Titan and we were very intrigued what that surface might be like because we knew that this planet has an unusual atmosphere. And therefore, its history could be quite different from the history of the inner planets or the satellites of Saturn, whose surfaces we see quite well. But unfortunately, when we got there, we discovered that the haze in the atmosphere is so thick that we can't see any detail on the surface. And if you look at this picture, you'll see that you can't see much detail at all.

This particular frame was taken in orange light, and in orange light, Titan looks like a fuzzy tennis ball. Now if we look at shorter wave lengths -- ultraviolet -- we can begin to see a few details. We notice that there's a dark polar cap. We see a slight difference in the contrast between the northern hemisphere and the southern. The northern hemisphere seems a bit darker, and this border here between the two hemispheres occurs just at Titan's equator. We don't know why that's true. Why is Titan telling us where its equator is? We're still trying to understand that.

If we move along and try to put together the pictures taken through the different filters, we can then reconstruct the color of this object and we see that it's rather orange. Again, if you look closely, you can detect the slight difference in brightness in the two hemispheres. We've also found that the entire satellite is surrounded by a high haze of particles. You can see that in this picture, which has used false color to demonstrate where the haze is by making it very blue.

NARRATOR
Titan's secrets, whatever they are, are guarded under a seemingly impenetrable layer of haze. But the Voyager team had had the foresight to equip their spacecraft with an infra-red spectrometer, an instrument designed to look through cloud layers by measuring the heat emitted from Titan. The infra-red spectrometer was the only hope of establishing where the surface of Titan actually is underneath its layers of cloud and haze.

The principles on which the instrument is based are straightforward. A prism separates ordinary white light into a spectrum with red at one end and blue at the other. Outside of these visible colors are other colors that our eyes cannot see. A thermometer placed in the blue end does not register, but right off the red end, the temperature goes up. This is infra-red and in these wave lengths different chemicals have their own unique colors or signatures which can be detected by the Voyager spacecraft and used to identify them. Methane, the same natural gas we burn on Earth, was long known to be a component of Titan's atmosphere. From a sample of methane, this infra-red spectrometer measures the intrinsic infra-red color of the gas and plots its characteristic signature as a graph. Every gas is different and can be identified, like methane, by its own unique infra-red signature.

TOBY OWEN
So this machine is plotting out the spectrum of Titan. And what it does first is to make the scale showing the temperature scale on the side and a frequency scale along the bottom, which is reproduced on the top as well. And now it's beginning to draw the spectrum of Titan. See...it starts off smoothly, and now it's beginning to show some features.

This funny wiggly line is just loaded with information. We start at this end with the rather smooth part of the spectrum. We come into these interesting features here, ending up here with methane, which we've just looked at in the laboratory. So this confirms what we've already known -- that methane is in the atmosphere.

Down here we find ethane, and acetylene, and this peak is very exciting. This is hydrogen cyanide, which hadn't been discovered before. It's exciting because hydrogen cyanide is a molecule that played a very important role in getting life started on the Earth. You can polymerize it to make adenine, which is one of the bases in DNA, the famous double helix, which gets us all going; and you can make amino acids if water is present, which was true on the Earth, but not on Titan. So I should make it clear that we're not saying that because we have found HCN in Titan's spectrum that we think life is beginning on Titan. But we do think that some of the chemistry on the Earth before life began is probably happening on Titan today. And if we could study it in more detail, we could learn something about pre-life chemistry on the Earth.

NARRATOR
Some source of energy is needed in Titan's atmosphere (seen here with false color enhancement,) to ensure that chemical processes can take place. But what is this source of energy which bonds chemicals together on Titan and may have fused the complex organic molecules that precede life?

This computer animation visualizes an important spacecraft measurement. It shows the protective magnetosphere which encloses all the inner moons except Titan. This is the region of space around Saturn dominated by the planet's magnetism. A wind of highly energetic particles from the sun is constantly bumping the protective magnetosphere in and out. These solar particles may be the source of Titan's exotic chemistry.

For Titan, entering the picture at top left, is sometimes exposed to them.

Perhaps these energetic particles of the solar wind are the spark that gets Titan's chemistry going. For it is in the upper atmosphere of Titan that the chemistry appears to be happening.

TOBY OWEN
So the substances which are forming high in Titan's atmosphere are some kind of organic material, which might be polymers of acetylene and hydrogen cyanide, polymers of the gases we detect in the spectrum. Then these things will gradually rain out of the atmosphere, a kind of slowly settling fog. We expect that the small particles will aggregate into larger ones and rain out onto the surface.

Now, as they get closer to the surface, they'll pass through a region where methane may condense in the atmosphere. So we may have clouds of methane and methane rain in fact on Titan, because in some respects, methane plays the same role in that atmosphere that water vapor does on Earth. So standing on the surface, we have this rain of methane perhaps in some areas ...we have these organic materials floating down -- manna from heaven, as it were -- and accumulating on the surface. So we might expect pools of the liquid methane with some of this gunk dissolved in them and the shores lined with it effectively. And the solid places would not be rock as we find on Earth or on the inner planets, but a combination of perhaps ices covered by this organic material. So it would be an extremely alien environment, totally different from anything we're accustomed to.

NARRATOR
In five thousand million years the sun will run out of hydrogen fuel and expand into a much larger star, a red giant. It will enlarge to engulf the Earth, which will cease to exist.

But Titan, further out, will warm up.

TOBY OWEN
And the whole satellite could begin to melt. So that huge amount of water that's now trapped as ice would begin to turn into an ocean. If conditions stabilized, it could stay as an ocean for some time. It might also just totally evaporate away and leave us with a small rocky core, rather like a large satellite or one of the rocky satellites of Jupiter.

NARRATOR
Sadly for Titan and any life that might just get started there, there will only be a few million years of warmth before the sun contracts to a tiny vestigial white dwarf. Then Titan will refreeze.

There are three known solid planets with atmosphere. This is Venus. Venus has a hot dry surface beneath its swirling clouds. This is known because the average temperature of the planet's surface varies considerably from place to place.

The Earth, on the other hand, has an ocean and polar caps. These smooth out the temperature differences at the solid surface and give our planet a quite distinctive signature. Planets with oceans have unique properties and can be recognized.

In March 1981, a new mathematical analysis of the Voyager I data was completed. It has revealed more about Titan. Most of the atmosphere is composed of nitrogen and it is thicker than the Earth's. Evidence is growing that Titan has not pools, but a huge ocean of liquid methane up to half a mile thick. At the poles, this liquid natural gas may even have frozen into methane ice. Perhaps if a spacecraft is ever sent to land on Titan, it will have to be a submarine.

In the geography of space, Titan is in our own backyard. Yet here is not only a vision of an Earth just before life began, but a growing conviction that if Titan is so near to life and so close to us, somewhere out there is a warmer Titan with life.

Voyager I did not take high resolution pictures of Saturn's outer moons Hyperion, Iapetus and Phoebe. Their secrets are still kept.

Now Voyager I's mission has been completed. The spacecraft is heading up and out of the solar system. Its next encounter is in 41,000 years' time with a star in Ursa Minor known as AC+793888. The twin spacecraft Voyager II, following one year behind on a different trajectory, encounters Saturn on August 25th, 1981.

PRODU

A BBC

Writt
FISHE

Narra
BILL

Produ
JULIE

Film
COLIN
JEANN

Film
EUGEN

Anima
IVOR

Sound
RON C

Graph
STEVE
KATI

Compu
JEANN

Film
PATTI

Edito
SIMON

A BBC/WGBH Boston Co-Production

Written, Produced, and Directed by
FISHER DILKE

Narrator
BILL MASON

Production Assistant
JULIE HARRUP

Film Editors
COLIN JONES
JEANNE JORDAN

Film Camera
EUGENE CARR

Animation Camera
IVOR RICHARDSON

Sound Recordist
RON CRABB

Graph Design
STEVE CONNELLY
KATI DAVIS

Computer Animator
JEANNE BLINN

Film Researcher
PATTI POLISAR

Editor
SIMON CAMPBELL-JONES

Special Thanks to:
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
United States Geological Survey
Lowell Observatory Arizona
European Space Agency
Dr. Robert B. Leighton
Dr. Charles Kohlase

Sound Mix
RICHARD BOCK

Coordinating Producer
THEA CHALOW

Production Unit Manager
SUSAN MOTTAU

Post Production Supervisor
TONY PRIANO

Assistant Unit Manager
DONNA RICE

Post Production Assistant
NANCY LINDE

Publicist
WILMA HILL

Production Secretary
QUEENE ANDERSON

Executive Producer
JOHN MANSFIELD

VIDEOTAPE/FILM copies of programs may be available for sale or rental, for audio-visual and broadcast use. For information, contact:

WGBH Distribution, 125 Western Avenue, Boston, MA 02134, (617-492-2777)

TRANSCRIPTS of programs+are available in bulk and individually from:

(Specify title of series)
(Specify title of program)
Box 1000
Boston, MA 02118

Bulk Rate:

20 or more copies of any one program transcript can be supplied for half the price of single copies. This offer is limited to programs broadcast since 1978.

Price: $1.50/copy for a minimum order of 20 copies of one transcript (please send payment with your order.)*

Individual Copies:

Programs from NOVA and other series seasons since 1978 are available in most cases as printed booklets. Transcripts of NOVA programs from 1974 to 1977 are available in most cases as 8½ x 11 photocopies.

Prices: $3/copy (1978-81)
$5/copy (pre-1978)

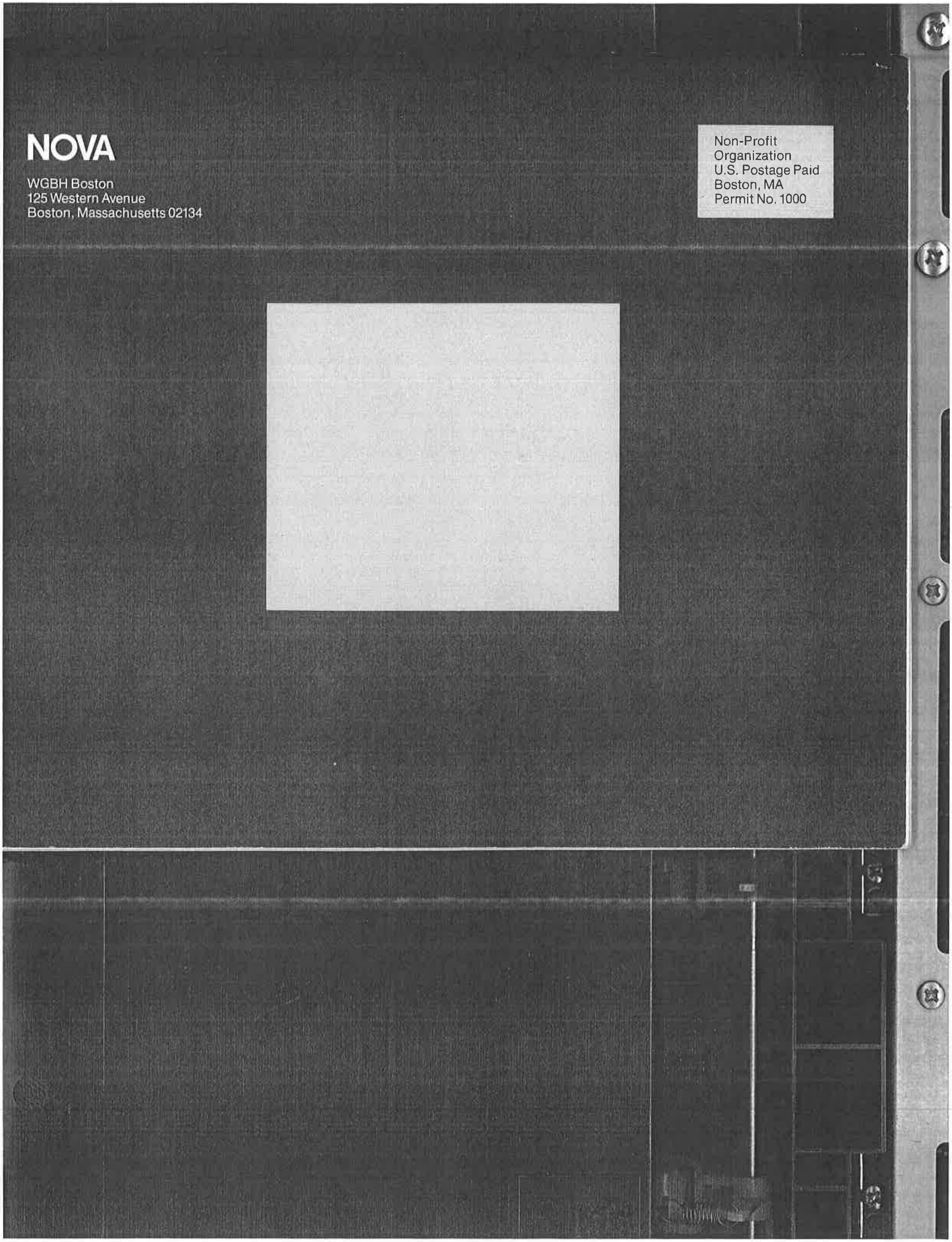
NOVA Subscriptions:

NOVA programs planned for the 1981-82 season are available by subscription. We will send you one copy of each of the 25 programs, to be aired weekly beginning in late September 1981 and continuing until April 1982. Copies will be mailed in the order in which the programs are broadcast by PBS; each new program transcript will be sent following that week's broadcast. NOVA ONLY!!

Price: $70 (8% less than the per-piece cost) (please send payment with your order.)*

**Please make checks payable to "WGBH Transcripts". Do not send cash.*

+For lists of titles available call or write WGBH Transcripts, 125 Western Avenue, Boston, MA 02134.(617)492-2777.



NOVA

WGBH Boston
125 Western Avenue
Boston, Massachusetts 02134

Non-Profit
Organization
U.S. Postage Paid
Boston, MA
Permit No. 1000