CONCLUSIONS

URANUS AMONG THE OUTER PLANETS

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This conference has offered us a rich and fascinating program. It is most unusual for an astronomical colloquium to include papers on social history, performances of music and readings of poetry, yet all of these apparent diversions have been entirely relevant to our principal topic. In commemorating the 200th anniversary of William Herschel's discovery of Uranus, we are simultaneously celebrating the special qualities of this musician turned astronomer, the extraordinary impact of his discovery on contemporary perceptions of Earth's place in the universe, the very recent growth in our knowledge about the planet itself, and our awareness that we shall soon be learning even more about Uranus from a spacecraft that is presently almost halfway there.

In this short review, I shall not try to summarize the many excellent papers presented at the conference. They are collected in this volume for all to read. Instead I would simply like to emphasize a few themes that have been embodied in these presentations, to try to place Uranus in perspective among the outer planets. The gaps in our present knowledge include some significant unsolved problems on which we can expect real progress in just the next five years.

There seem to be several lessons to be learned from Herschel's discovery of Uranus. The one most often mentioned is the importance of systematic and meticulous observations. We have seen a modern proof of this assertion in the discovery of the planet's rings by James Elliot and his colleagues. These astronomers were not looking for rings, nor was Herschel looking for a planet. But in each case the extent and quality of the observations were sufficient to make the discovery possible.

https://doi.org/10.1017/S025292110008249X Published online by Cambridge University Press

Another message Herschel left us was the importance of good instrumentation. The telescopes that he produced, as we have heard, were among the best in the world in their optical quality. He insisted on this, and spent great effort achieving it. We find ourselves carrying out this same tradition in the form of large consortia of scientists, rather than as single individuals. In a few years, the most powerful telescope ever built will be sending the data it gathers from Earth-orbit to astronomers on the ground. One of the early targets of this instrument - the Space Telescope - will surely be the planet Herschel discovered. As Dr. Caldwell and Dr. Stone have told us, this telescope will provide the best images of Uranus that we will have for a few months before the Voyager spacecraft reaches the planet in January of 1986.

The last lesson I would like to mention comes from the attitude of other people associated with the discovery. At the time Herschel found Uranus, he was essentially an unknown amateur. He thought he had found a comet, not a new planet. How easy it would have been for the established, professional astronomers to have taken credit for the discovery, since it was up to them to prove that the new object was indeed a planet. So we can admire the generosity of spirit of Nevil Maskelyne, who made certain that full credit was in fact given to William Herschel.

What have we learned about Uranus since Herschel's time? I obviously cannot offer a personal perspective that spans 200 years, but I can at least cover the last 20. Most of what we know about Uranus has been learned very recently. The high quality of this conference is an eloquent testimony to that fact: there are probably more scientists studying Uranus today than the total number who ever spent time seriously thinking about the planet before 1961. At that time, we knew that Uranus had a deep hydrogen atmosphere. Ten years earlier, Gerhard Herzberg had successfully identified one of the pressure induced dipole absorptions of hydrogen in the planet's spectrum as recorded by Gerard Kuiper. This was in fact the first detection of hydrogen in a planetary atmosphere. The strong absorptions seen in the visible spectrum since the early visual studies of William Huggins in the 19th century had been identified with methane by Rupert Wildt and confirmed and extended by Arthur Adel and V. M. Slipher in the 1930's. The major spectroscopic puzzle in 1961 was the identification of five regularly spaced lines near 7500 Å, which turned out to be caused by methane. The only (apparently!) well-known quantity at that time was the planet's rotation period which, as we have heard in Dr. Goody's excellent review, was thought to be $10^h\ 49^m$. Clearly if we had held this meeting in 1961, it would have been a very short one!

To see what we know now, one can consult the Proceedings in this volume. As a way of underlining some of the important characteristics of Uranus, it is helpful to draw up a list of those properties that make the planet unique. For many years, it has been customary to divide the outer planets into two groups by bulk properties: Jupiter and Saturn were assumed to be very similar to each other and to the composition of the primordial solar nebula, while Uranus and Neptune seemed to be another similar pair which differed from their giant neighbors by having much less hydrogen and helium. But we have learned in just the last few years that these two outer planets are very different from each other; the papers presented at this conference have strongly underlined this distinction. A personal list of properties unique to Uranus is given in the accompanying Table.

Let us briefly go through these in turn. The near-alignment of the planet's rotational axis with the orbital plane must produce unusual effects on the circulation and/or chemistry of the portion of the atmosphere that responds to solar insolation. We have just seen evidence of a delayed seasonal response in an outer planet atmosphere in the pictures of Titan returned by Voyager 1. We may be witnessing some aspects of the reaction of Uranus to its unique orientation in the microwave observations that have been collected during the past decade. As Dr. Axford has emphasized in his comprehensive discussion, the effects of this orientation on the interaction of Uranus with the solar wind are more difficult to evaluate, since we presently have no measurement of the planet's magnetic field. The Voyager 2 spacecraft will provide us with the necessary data to understand both of these effects when it encounters Uranus in 1986.

Neptune is now the only outer planet not known to have a ring system. But the rings of Uranus are distinctly different from those of either Jupiter or Saturn, being both narrower and darker. The theory of Peter Goldreich and Scott Tremaine, advanced to explain these rings, has found observational verification to first order with the Voyager 1 observations of Saturn's F-ring. Yet there are still problems to be resolved, as Drs. Brahic, Dermott, and Elliot have emphasized. We may anticipate new observational data from forthcoming stellar occultations, even before Voyager 2 arrives.

Uranus is presently the only outer planet with no known satellites in retrograde orbits. Since such satellites are often thought of as captured objects in the systems where they occur, and since we now have evidence of at least one unattached object, Chiron, roaming the space between Uranus and Saturn, the absence of any retrograde body about Uranus is intriguing. Perhaps this absence is associated with the planet's unique axial alignment. Or perhaps we should emphasize the word presently in this discussion, since the search for faint satellites in this system has not been pushed as hard as it could be. Six satellites were added to the Saturn system in just the last two years!

But we can be quite certain that there is no large satellite - nothing as big as the Galilean moons of Jupiter, with Titan, or with Triton. To try to understand the reason for this anomaly, we must first find out more about the moons that do exist, to see how they compare in composition and surface histories with the other satellites we know.

Uranus is the only outer planet that has not been found to radiate more energy than it receives from the sun. One could reconcile this with Jupiter and Saturn in terms of a basic difference in composition and internal structure. It becomes a more subtle problem with the awareness that Neptune does have an internal source of energy. One must look to differences in formation histories for a possible answer.

The observed variability of the microwave radiation with time may be related both to the orientation of the planet's axis and to the absence of a deep seated energy source. Somehow, one must explain an apparent change in microwave opacity as the pole of rotation is turned toward the observer. We have still only seen less than 25% of the cycle, so even this correlation is not secure. Observations during this decade will provide the necessary leverage.

The upper troposphere of Uranus seems reasonably cloud free. This condition was thought to obtain for both Uranus and Neptune until a few years ago, when distinct "weather patterns" were deduced for Neptune on the basis of observations of periodic variations in the strengths of infrared absorption bands. Nothing comparable has been seen on Uranus. Evidently the temperature lapse rates in the atmospheres of these two planets are distinctly different, a point that is emphasized in another way by the fact that Uranus does not exhibit strong emission bands from ethane and methane in the 8-15μm region. All the other outer planets (including Titan) show evidence of an upper atmosphere thermal inversion this way. Why Uranus does not remains a puzzle. Is it the axial orientation? The absence of internal heat? Some basic difference in atmospheric composition? We simply don't know.

Having emphasized these unique properties of Uranus, I should reiterate that kinship with Neptune is still manifested in that both planets are deficient in hydrogen relative to Jupiter and Saturn. This difference is revealed most clearly in the bulk mean densities of the four objects. There is still controversy - as exhibited in papers presented here - about the methane mixing ratios in the atmospheres, which might be expected to reveal the same effect. This is another area where I think progress can be made before the Voyager 2 encounter.

Dr. Hubbard has raised the interesting possibility that both planets may have formed from comet-like planetesimals and could therefore have atmospheres containing no helium. (Since Herschel at first thought he had found a comet when he sighted Uranus, this evolutionary sequence would probably please him.) An

https://doi.org/10.1017/S025292110008249X Published online by Cambridge University Press

associated problem is posed by the excess microwave radiation exhibited by both planets in the 2-10 cm range, as described by Dr. Gulkis. If Uranus alone exhibited this feature, one might be inclined to attribute it to the conversion of NH_3 to N_2, as observed on Titan. But to find it on Neptune too, where an internal heat source should keep the troposphere mixed, makes this possibility less likely. A basic difference in the relative abundances of nitrogen and sulfur might be associated with formation from comet nuclei. On the other hand, Dr. Belton's provocative suggestion that Uranus might have a solid surface at a pressure of just a few tens of bars could allow a photochemical explanation to remain viable, if he turns out to be correct.

This brief survey should provide some indication of the progress we have made in understanding Uranus and its place in the solar system since Herschel's day. We might emphasize how much is left for us to do by mentioning three areas where there has been little advance. We still do not know what Uranus really looks like. We have scattered images of various qualities taken at different wavelengths, including the excellent set obtained by Robert Danielson from a telescope carried by a high-altitude balloon. Good as these Stratoscope images are, they are extremely limited in both the wavelength and time domains. This is one of the reasons that we are still uneasy about such questions as the period of rotation and the presence of clouds and hazes. Given his emphasis on high-quality telescopes, Herschel might be surprised that our own planet's atmosphere has proved to be the limiting factor in obtaining better resolution. He would surely be as delighted as we are at the prospect of the Space Telescope.

In an entirely different realm, it is sobering to realize that only one paper at this conference was delivered by a woman. I think that would have been a surprise to Caroline Herschel. Devoted as she was to her brother, her own accomplishments would surely have led her to expect that women would be playing a more prominent role in astronomy by this time. Her career is a challenge to us to make such opportunities more available.

Finally, we are still coping with the wonderful cosmogonic problem this planet poses: What combination of processes set it spinning in such an unusual way? It may be that we shall never be able to find a unique answer to this question. But we can expect a rich harvest of data during the next few years from the wide variety of ground-based and near-Earth techniques represented at this conference even before the Space Telescope and Voyager observations are made in 1985 and 1986. So we may harbor the hope that when we assemble again in five years time to discuss this fascinating planet, some real progress will have been made in all three of these areas.

Yet as we anticipate our own interest in the new understanding of Uranus we will have then, we might pause to consider again the impact of Herschel's discovery on the people of his time. We have become rather spoiled with new results because of the many splendid accomplishments of the program of planetary exploration during this last decade. Descriptions of new phenomena or intriguing pictures of distant planets seem to come along every year or two. But in Herschel's day, life did not move at such a pace. Finding a planet beyond those known to everyone was an extraordinary discovery. As just one example, it supplied John Keats with an image expressing his feelings of wonder and delight in his famous sonnet on Chapman's Homer:

"Then felt I like some watcher of the skies
When a new planet swims into his ken ..... "

I am sure we will have many more opportunities to experience these same feelings as we continue our investigations of this distant and surprising world.

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UNIQUE PROPERTIES OF URANUS

(As of March 1981)

Orientation of Rotational Axis

Meteorology

Magnetosphere

Nine Dark, Narrow Rings

No Known Retrograde Satellites

No Large Satellite (R > 1500 km)

No Detectable Internal Heat Source

Time-Variable Microwave Emission

No Thick Upper Troposphere Clouds or Hazes

No Detectable High Altitude Emission