Reports

Uranus: Variability of the Microwave Spectrum

Abstract. *Radio astronomical observations of Uranus show that the radio emission spectrum is evolving in time. Ammonia vapor must be depleted in the Uranian atmosphere as Gulkis and his co-workers previously suggested. Since 1965, ammonia either has been decreasing in time or is a decreasing function of latitude, or both, provided that the radio emission is atmospheric in origin. If Uranus has an observable low-emissivity "surface," these trends may be reversed. The microwave observations made in 1965, at the time when the spin axis of Uranus was nearly perpendicular to the sun-Uranus line, are consistent with an atmospheric opacity profile that would be produced by saturated ammonia vapor in a predominantly hydrogen atmosphere. At the present time, when the spin axis of Uranus is nearly aligned with the sun-Uranus line, the measurements require an opacity that would be produced by saturated water vapor. A large thermal gradient between the pole and equator is ruled out.*

Uranus is approximately 50 K warmer than both Jupiter and Saturn in the 1.5- to 3-cm wavelength range, despite its greater distance from the sun. To explain this difference, Gulkis *et al.* postulated (*1*) that NH_3 must be depleted in the Uranian atmosphere. They estimated that the NH_3 mixing ratio must be less than 10^{-6} in the temperature range from 150 to 200 K if the atmosphere is in convective equilibrium. This is less by two orders of magnitude than the expected mixing ratio based on solar abundances. No such depletion is predicted from the observed microwave disk temperatures of Jupiter and Saturn.

Klein and Turegano later discovered (*2*) that between 1966 and 1978 the flux density of Uranus was increasing in the wavelength range from 2 to 3.6 cm. Subsequent measurements (*3–5*) have confirmed the variability and shown that it extends to longer wavelengths. Observations at millimeter wavelengths have also been made (*6, 7*).

We present arguments here in support of the view that the most likely source of the microwave variability is a change in the opacity of the atmosphere, probably related to the large inclination of Uranus's rotational axis (*8*). We show that NH_3 in the Uranian atmosphere must be depleted as a function of either time or latitude. The microwave opacity of water vapor may be playing an important role in shaping the microwave temperature spectrum.

A number of mechanisms have been considered to explain the time variability. These include (i) synchrotron emission from a radiation belt around Uranus, (ii) thermal emission from the Uranian rings, (iii) the changing solid angle of Uranus due to its oblateness and tilted axis, (iv) atmospheric temperature variations with time or latitude (that is, equator-to-pole temperature gradient), and (v) atmospheric opacity variations with time or latitude. The first three mechanisms are ruled out on the basis of observations. Briggs and Andrews (*3*) found that no emission is observed outside of the visible disk at 6-cm wavelength. The solid angle is virtually constant because the oblateness is only 0.03 (*9*). Briggs and Andrews argued (*3*) that a permanent equator-to-pole temperature gradient sufficient to explain the time variability was inconsistent with their maps of the planet at 6-cm wavelength. The remaining possibilities are that the temperature or the opacity of the atmosphere is changing, or both.

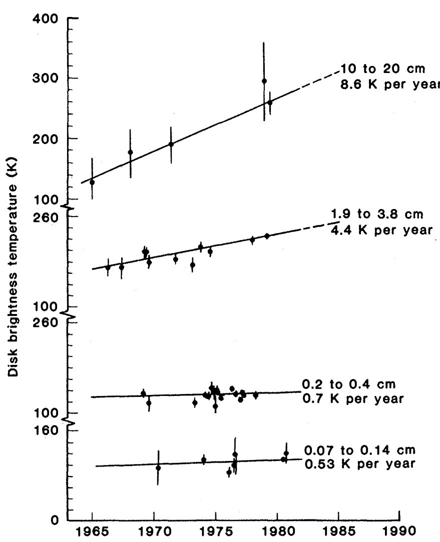

Fig. 1. Variations in the observed disk temperatures of Uranus for four wavelength intervals. The weighted least-squares fit to a linear variation in time is shown for each interval.

In order to understand better the variability of the brightness temperature spectrum over the microwave wavelength range from ~ 1 mm to ~ 20 cm, we divided the data available to us into four groups according to wavelength interval. The raw data were taken over a long period (> 15 years) by numerous observers. The data we used are (i) those contained in the compilation by Gulkis *et al.* (*1*); (ii) the recent centimeter measurements reported by Klein and Turegano (*2*), Briggs and Andrews (*3*), Conway (*4*), and Batty *et al.* (*5*); (iii) the millimeter measurements reported by Ulich (*6*); and (iv) several prepublication measurements at submillimeter wavelengths (*7*). The wavelength intervals used were selected somewhat arbitrarily, according to the availability of observational data. Each group was confined to have a wavelength range < 2 so as to minimize the wavelength dependence of the variability within a given group. The grouped data show that the observed disk brightness temperatures of Uranus have been increasing with time since 1965 and that the rate of increase is greatest at the longest wavelengths.

We can estimate how the radio spectrum of Uranus is evolving by assuming that the time variations in each interval are linear. The weighted least-squares linear fit to each of the four intervals leads to temperature drift rates of 0.53 (±1.0), 0.7 (±1.0), 4.4 (±0.9), and 8.6 (±1.5) K per year for the shortest to longest wavelength intervals, respectively (Fig. 1). The uncertainties associated with the data in the two shortest wavelength intervals are consistent with a zero drift rate, whereas the two longest wavelength intervals show a statistically significant drift rate. The average temperature at each of the four wavelength groups was interpolated from Fig. 1 at 5-year intervals between 1965 and 1980. The results (Fig. 2) give a schematic representation of the evolution of the microwave temperature spectrum. An extrapolation to 1985, the next time when the sun reaches its most northernly latitude on Uranus, is also shown.

A variable atmospheric temperature can be ruled out as a source of the variability at radio wavelengths. Measurements in our two shortest wavelength intervals are sensitive to the physical temperature of the atmosphere since the primary source of opacity at millime-

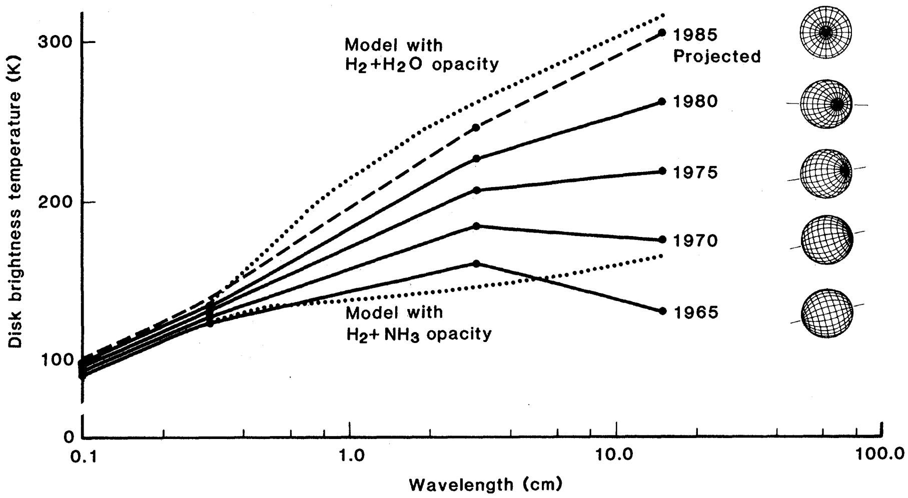

Fig. 2. Schematic evolutionary spectra for Uranus. The dotted lines are theoretical spectra for which it is assumed (upper curve) that water vapor and H_2 are the only sources of the microwave opacity and (lower curve) that the only sources are NH_3 and H_2. The dashed line is a linear extrapolation of the variation to 1985, the next time at which the polar heating will reach a maximum.

ter wavelengths is H_2, the dominant atmospheric constitutent. Since no significant variability is observed in this wavelength range, we conclude that the atmosphere is not simply warming. At deeper levels in the atmosphere, the heat capacity is sufficiently large that it is unlikely that the average physical temperature could change by more than a few degrees (Kelvin).

To study the effects of variations in atmospheric opacity, we computed opacity profiles corresponding to the brightness temperatures at different epochs. For this purpose, we adopted a model atmosphere based primarily on infrared observations and assumed that the atmosphere is in convective equilibrium at depth (*10*). This model is similar to atmospheric models derived by Wallace (*11*), Appleby (*12*), and others. These derived opacity profiles lie between what would be expected in an atmosphere that contains saturated NH_3 vapor and one that contains saturated water vapor. Calculated spectra for these models are shown in Fig. 2. Solar concentrations of nitrogen and oxygen are assumed.

One interpretation of the data is that the microwave opacity of the Uranian atmosphere is large in the equatorial region and small over the poles. This restricts the radio emission from the equatorial regions to the higher and colder portions of the atmosphere; the polar regions, having lower opacity, give rise to radio emissions from the deeper and warmer portions of the atmosphere. To account for the higher temperatures observed, the microwave opacity over the polar regions would need to be considerably less (in the pressure range of 10 to 100 atm) than that provided by saturated NH_3. A model atmosphere in which water vapor is present (and NH_3 is absent) appears to be consistent with the higher temperature observations.

Briggs and Andrews have suggested (*3*) that the increased polar heating that occurs seasonally may reduce convection over the poles and thereby allow the (polar) NH_3 to be depleted. This model seems attractive and suggests that some quantitative work be done to establish time scales for depletion of NH_3 and mechanisms to limit the convection. Our results show that the depletion is most severe in the temperature range from 200 to 300 K. Since this is the region in which Weidenschilling and Lewis predict the presence of NH_4SH and H_2O clouds (*13*), it may be that these clouds are somehow related to the depletion process.

Another possible explanation of the variability is that the microwave opacity of the Uranian atmosphere is low in the equatorial region, thereby allowing emission from a "surface" to dominate when the planet is viewed perpendicular to the rotation axis. If the "surface" emissivity is less than unity, the planet would appear cold as it did in the mid-1960's. Over the polar regions, the atmospheric opacity could be higher and the "surface" emission unimportant. The brightness temperatures of the poles would then refer to the physical temperatures of the atmosphere, and the planet would appear warmer. This effect is frequently observed by downward-looking microwave receivers in orbit above Earth's oceans. There is little evidence at this time that Uranus has a solid surface; however, a thick water cloud on Uranus, as suggested by Weidenschilling and Lewis (*13*), might produce the same effect.

An unambiguous interpretation of the data does not seem possible at this time. However, we believe our modeling studies support the following general conclusions. (i) H_2 is the predominant absorber at millimeter wavelengths, but additional absorbers are required to explain the microwave spectrum at longer wavelengths; (ii) the opacities required to explain the time variability of the spectrum at centimeter wavelengths are bounded by opacity profiles that could be produced by a saturated NH_3 vapor model and a saturated water vapor model; (iii) the observations are consistent with a model atmosphere in which saturated NH_3 is present over the equator of Uranus, but NH_3 is reduced at high latitudes; and (iv) the most recent observations of Uranus's polar latitudes are consistent with the explanation that the opacity is due to saturated water vapor.

Continued monitoring of the brightness temperatures of Uranus over a broad range of wavelengths is important, especially over the next several years as the pole passes through the planet-sun line. Knowledge of the pole-to-equator distribution of emitted and scattered radiation should help us to understand the variability. If our evolutionary model is correct, we would expect to see the brightness temperatures at centimeter wavelengths reach a maximum in the near future and then start to decline. Long wavelength measurements of Uranus along with additional modeling will be particularly useful in detecting the presence or absence of a "surface" or thick liquid cloud.

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References and Notes

1. S. Gulkis, M. A. Janssen, E. T. Olsen, *Icarus* **34**, 10 (1978).
2. M. J. Klein and J. A. Turegano, *Astrophys. J.* **224**, L31 (1978).
3. F. H. Briggs and B. H. Andrews [*Icarus* **41**, 269 (1979)] found that less than 10 percent of the total radio flux originates outside the visible disk of Uranus.
4. R. G. Conway, *Mon. Not. R. Astron. Soc.* **190**, 169 (1980).
5. M. J. Batty, D. L. Jauncey, P. T. Rayner, S. Gulkis, *Astrophys. J.* **243**, 1058 (1981).
6. B. L. Ulich, *Astron. J.* **86**, 1619 (1981).
7. G. S. Orton made available prepublication submillimeter wave brightness temperature data for Uranus.
8. The north pole of Uranus is inclined ~ 98° to the

ecliptic plane, and the seasons on Uranus average 21 terrestrial years in length. During 1966, the axis of Uranus was practically in the plane normal to the solar radius vector, all parts of the planet "seeing" the sun during one rotational period. In 1985, the north pole of Uranus will face the sun continuously.
9. J. L. Elliot, E. Dunham, L. H. Wasserman, R. L. Millis, J. Churms, *Astron. J.* **83**, 980 (1978).
10. The assumption of an adiabatic lapse rate in the atmosphere is open to question since Uranus may not have an internal heat source [L. Trafton, *Rev. Geophys. Space Phys.* **19** (No. 1), 43 (1981)].
11. L. Wallace, *Icarus* **43**, 231 (1980).
12. J. F. Appleby, thesis, State University of New York at Stony Brook (1980).
13. S. J. Weidenschilling and J. S. Lewis, *Icarus* **20**, 465 (1973).
14. This research was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Ediacaran (Precambrian) Fossils from the Wernecke Mountains, Northwestern Canada

Abstract. *Fossil medusoids identified as* Cyclomedusa davidi?, Beltanelliformis brunsae, *and cf.* Sekwia excentrica *are reported from Late Precambrian strata in the Wernecke Mountains. They are representatives of the Ediacaran fauna, the oldest assemblage of cosmopolitan metazoans, and are only the third such occurrence in Canada. In addition, specimens broadly resembling the problematic structure* Rugoinfractus ovruchensis, *previously known only from the Precambrian of the Ukraine, are reported from the Lower Cambrian of the nearby Mackenzie Mountains.*

The term "Ediacaran fauna" refers to a Late Precambrian assemblage of fossils of soft-bodied animals, mainly coelenterates and annelids, first discovered in the Ediacara Hills of South Australia. This fauna represents the earliest abundant record of metazoan life and underlies what is presently the oldest Paleozoic system, the Cambrian, which is characterized by the development of animals with hard parts. Sparse but nevertheless worldwide finds of the Ediacaran fauna have prompted a call for an Ediacaran (or Ediacarian) Period and System (*1–3*). While a decision on this proposal must await judgment by the geological community, there is a current need to demonstrate the fauna's geographic and stratigraphic distribution and its limits in terms of evolution. We report here a favorable new region in which to search for Ediacaran fossils and describe and illustrate some specimens collected in July 1982.

The geographic location and stratigraphic position of the fossils are shown in Fig. 1. Section 1, located in the Wernecke Mountains, Yukon Territory, represents the local stratigraphy at and near three of the fossil localities. Composite sections 2 and 3 in the nearby Mackenzie Mountains, Northwest Territories, represent a fourth locality as well as other previously reported fossil localities (*4, 5*) that are relevant to this discussion. The approximate location of the Precambrian-Cambrian boundary in the two sections is based on current work by W.H.F. and G.M.N. on trace fossil ranges.

Evidence for a small late Precambrian faunal assemblage in the Mackenzie Mountains was reported by Fritz (*4*) and later confirmed by Hofmann (*5*). The biota includes the coelenterates *Inkrylovia* Fedonkin and *Sekwia* Hofmann, the trace fossils *Gordia* Emmons and *Torrowangea* Webby, and problematic remains. We now confirm the presence of additional representatives of the Ediacaran fauna in the post-tillite, Late Precambrian sequence of the the Wernecke Mountains. These comprise the medusoids *Cyclomedusa davidi?* Sprigg, *Beltanelliformis brunsae* Menner, and cf. *Sekwia excentrica* Hofmann. We also recovered remains from the lower Cambrian in the Mackenzie Mountains that broadly resemble *Rugoinfractus ovruchensis* Paliy, reported from the Middle Riphean of the Ukraine; these were considered by Paliy (*6*) and Durham (*7*) to be undoubted trace fossils and by Cloud and Glaessner (*2*) to be shrinkage crack fillings.

Fossils referred to *C. davidi?* Sprigg (Fig. 2, A and B) comprise centimetric, circular to subcircular medusoid impressions on a bedding plane of a light brown weathering, greenish-gray, fine-grained, argillaceous sandstone belonging to an unnamed formation. The 15 specimens in Fig. 2A distinct enough to be measured are disks 1.7 to 7.0 cm in diameter (mean, 4.0 cm) characterized by moderately developed concentric rugae and a distinct central depression several millimeters across with a relief 1 to 3 mm higher than that of the rugate portion. The largest specimen (Fig. 2B) has delicate, uniformly spaced, radial striae in an inner annular zone between the central depression and the outer rugae; its outer margin is broadly indented on one side, and on the opposite side it is deformed because of the superposition and impression of another specimen that is slightly smaller and much more poorly preserved. These features indicate that the disks are the impressions of independent, cohesive, organized pliable bodies and rule out a nonbiological origin for them. The size, circular outline, concentric rugae, central structure, and radial striae of our fossils correspond to the characteristics of *Cyclomedusa* Sprigg. The forms are closest to *C. davidi* Sprigg, although the rugae are not as coarse as in some typical Australian specimens. We therefore tentatively assign our fossils to Sprigg's species.

Beltanelliformis brunsae Menner (Fig. 2C), also interpreted as medusoid impressions, is represented by centimetric round protuberances on the surface of bedding planes of medium-grained, cross-laminated sandstone in contact with dark gray mudstone. The protuberances are 1 to 2 cm across and 1 to 3 mm high and exhibit delicate peripheral and transverse wrinkles. The central portion of individuals is flat to very gently undulating, whereas the margin is moderately to steeply sloped, giving the structures the appearance of short, truncated cones. The forms most closely resemble the structures illustrated by Fedonkin (*8*) from the Valdai Series (Vendian) of the Onega Peninsula on the White Sea.

A single specimen of a third type of structure (Fig. 2D) resembles the fossil medusoid *S. excentrica* Hofmann, which is found slightly lower in the stratigraphic sequence in section 2 (*5*). It is a subcircular depression, about 2.2 cm across and 1 mm deep, from a brownish-gray weathering, medium-grained, micaceous sandstone. The specimen has faint eccentric markings and an indistinct annular depression at the margin. Since the preservation is poor and only one specimen is available, our identification is incomplete.

Lastly, under cf. *R. ovruchensis* Paliy, we record remains of rounded, oblong structures with apparent bilateral symmetry and tripartite organization (Fig. 2E) occurring in greenish-gray to purple, medium-grained, micaceous sandstone at section 2. The structures are found in a succession containing abundant trace fossils and are stratigraphically above levels with *Protohertzina* cf. *P. anabarica* Missarzhevskiy (*9*) and *Phycodes pedum* Rud. Richter (*4*) and 340 m below the top of the *Fallotaspis* Zone. They are thus probably of Early Cambrian age. The forms are preserved as sand fillings