Reports

Remote Sensing of the Magnetic Moment of Uranus: Predictions for Voyager

Abstract. *Power is supplied to a planet's magnetosphere from the kinetic energy of planetary spin and the energy flux of the impinging solar wind. A fraction of this power is available to drive numerous observable phenomena, such as polar auroras and planetary radio emissions. In this report our present understanding of these power transfer mechanisms is applied to Uranus to make specific predictions of the detectability of radio and auroral emissions by the planetary radio astronomy (PRA) and ultraviolet spectrometer (UVS) instruments aboard the Voyager spacecraft before its encounter with Uranus at the end of January 1986. The power available for these two phenomena is (among other factors) a function of the magnetic moment of Uranus. The date of earliest detectability also depends on whether the predominant power source for the magnetosphere is planetary spin or solar wind. The magnetic moment of Uranus is derived for each power source as a function of the date of first detection of radio emissions by the PRA instrument or auroral emissions by the UVS instrument. If we accept the interpretation of ultraviolet observations now available from the Earth-orbiting International Ultraviolet Explorer satellite, Uranus has a surface magnetic field of at least 0.6 gauss, and more probably several gauss, making it the largest or second-largest planetary magnetic field in the solar system.*

Ultraviolet observations of Uranus from the Earth-orbiting International Ultraviolet Explorer (IUE) spacecraft (*1–3*) have provided what is probably the first remote detection of that planet's magnetosphere. Combining these observations with a specific physical mechanism for powering the aurora (*4*) allows us, in principle, to estimate the planet's magnetic moment before the encounter of the Voyager spacecraft with Uranus in January 1986. We assess here the prospects for remote detection of the magnitude of the magnetic moment of Uranus (rather than its mere existence) in terms of appropriate physical models combined with Voyager approach observations.

In addition to auroral emissions, the magnetospheres of Earth, Jupiter, and Saturn produce radio emissions that are detectable at large distances (*5*). By comparing the average radio emission intensities of the three planets, Desch and Kaiser (*6*) inferred the existence of a scaling law, which they call a radiometric Bode's law, whereby the low-frequency radio emission from each planet consumes 3×10^{-6} to 6×10^{-6} of the solar wind power incident on its magnetosphere. The terminology stems from an earlier empirical relation known as the magnetic Bode's law (*7*), whereby the magnetic moment of a planet is taken to be proportional to the angular momentum of its spin. This hypothesis was first proposed by Blackett (*8*), and we refer to it as Blackett's law.

We shall adopt the simplest form of Blackett's law, in which the nominal magnetic moment of a given planet is scaled from the terrestrial value in proportion to the quantity $mR^2\Omega$, where m, R, and Ω are planetary mass, radius, and spin frequency, respectively. (Somewhat different results are obtained if one attempts to account for variations in the radial mass distribution in the planetary interiors or if one scales to Jupiter or Saturn rather than Earth.) Adopting the values $m_U = 8.67 \times 10^{25}$ kg $= 14.5\ m_E$, $R_U = 26{,}200$ km $= 4.11\ R_E$, and $\Omega_U = 1.1 \times 10^{-4}$ rad/sec $= 1.51\ \Omega_E$, we obtain a nominal Blackett's law value for magnetic moment of Uranus M_B of $\sim 1.7\ GR_U{}^3$ (subscripts U and E refer to Uranus and Earth, respectively). A similar value, combined with the radiometric Bode's law under the assumption of isotropic emission, leads to the expectation (*6*) that Voyager will detect radio emission from Uranus during early 1985.

In their formulation of the radiometric Bode's law, Desch and Kaiser (*6*) adopted an Earth-like model in which the magnetic moment affects power input only through its influence on the magnetosphere's cross-sectional area for intercepting the solar wind. Available power then scales as the 2/3 power of M, the planetary magnetic moment. An alternative model, the disk-dynamo model, has been proposed (*4*) for the interaction of the solar wind with the magnetosphere of Uranus. In this model available power scales instead with the 4/3 power of the magnetic moment. In either case the overall efficiency with which available power is converted into auroral emissions is known to be small ($\lesssim 10^{-2}$). To the extent that one can estimate this efficiency, one can derive a scaling law between planetary magnetic moment and auroral luminosity. By combining this scaling law with auroral luminosity inferred from the IUE observations, one can predict the magnetic moment of Uranus and the most likely time for the first detection by Voyager of radio and ultraviolet (UV) emissions from the planet.

In an Earth-like magnetosphere power is extracted from the solar wind to drive a magnetospheric convection system that results in energization of auroral particles. The power delivered to the aurora is

$$P_E = \epsilon_E \rho v^3 A/2 \qquad (1)$$

where ϵ_E is the overall efficiency with which incident solar wind power is converted to auroral luminosity in an Earth-like system, ρ and v are the mass density and velocity of the solar wind, and A is the cross-sectional area of the magnetosphere. The distance from the center of the planet to the stagnation point of its magnetosphere is

$$R_m = (2M^2/\mu_0 \rho v^2)^{1/6} \qquad (2)$$

The magnetospheric cross-sectional area is

$$A \approx 4\pi R_m{}^2 \qquad (3)$$

which, with Eq. 1, gives the scaling law

$$P_E \approx 2\pi(2/\mu_0)^{1/3} \epsilon_E \rho^{2/3} v^{7/3} M^{2/3} \qquad (4)$$

for an Earth-like magnetosphere.

For the disk-dynamo model the corresponding expression is

$$P_d = (16\pi/3)(2\mu_0)^{-2/3} \epsilon_d \rho^{1/3} v^{-1/3} \Omega^2 M^{4/3} \qquad (5)$$

where Ω is planetary spin frequency and ϵ_d is the overall efficiency with which power is extracted from planetary rotation by the disk-dynamo interaction and converted into Lyman α (Lyα) emission (*4*).

It is useful to compare the total power available to drive magnetospheric processes by the two mechanisms under consideration. For this purpose it is convenient to normalize the magnetic moment by the value M_0 that would just stand off the solar wind at the planetary surface:

$$M_0 = R_p^3(\mu_0\rho v^2/2)^{1/2} \quad (6)$$

(as obtained from Eq. 2 with $R_m = R_p$, the planetary radius), and to normalize the power by the amount P_0 of solar wind power that would be intercepted by the planetary cross section

$$P_0 = \rho v^3 \pi R_p^2/2 \quad (7)$$

With these definitions the total power available from the two processes can be written

$$\max P_E/P_0 = (M/M_0)^{2/3} \quad (8)$$

for the Earth-like model (setting $\epsilon_E = 1$ in Eq. 4) and

$$\max P_d/P_0 = (2^{11/3}/3)(\Omega R_p/v)^2(M/M_0)^{4/3} \quad (9)$$

for the disk-dynamo model (setting $\epsilon_d = 1$ in Eq. 5). The ratio of powers available from the two processes is

$$(\max P_d)/(\max P_E) = (2^{-2/3}/3)(\Omega R_T/v)^2 \quad (10)$$

where

$$R_T = 2^{7/6} R_p(M/M_0)^{1/3} \quad (11)$$

is the radius of the magnetospheric tail (*4*). Thus the disk-dynamo interaction is competitive with the Earth-like solar wind interaction if the corotation speed at the tail boundary is comparable to or greater than the solar wind speed (*4*). For example, if we adopt a typical solar wind speed v = 400 km/sec, a rotation rate for Uranus $\Omega = 1.1 \times 10^{-4}$ rad/sec (*9*), and $M_B = 1.7\ GR_U^3 = 1.1 \times 10^5\ M_0$, then Eq. 11 gives $R_T = 110\ R_p$ and Eq. 10 gives $(\max P_d)/(\max P_E) = 0.12$. If the disk-dynamo is more efficient than the Earth-like mechanism by a factor of 10, then the magnetospheric power inputs from the two processes would be about equal. Thus, notwithstanding the uncertainty in estimating the respective efficiency factors, we cannot rule out one mechanism in favor of the other.

The overall efficiency factor (ϵ_E or ϵ_d) is the product of (i) the efficiency ϵ_1 with which the magnetosphere extracts power from the solar wind in the Earth-like interaction or with which the solar wind extracts power from planetary rotation in the disk-dynamo interaction, (ii) the efficiency ϵ_2 with which this magnetospheric power is utilized to precipitate auroral primary particles into the atmosphere; and (iii) the efficiency ϵ_3 with which the atmosphere converts the incident primary particle energy flux into escaping auroral (Lyα) radiation. The individual efficiency factors can be estimated with an uncertainty of perhaps a factor of 2; such uncertainties are multiplicative, resulting in an uncertainty of almost one order of magnitude in the overall efficiency that we need in order to relate auroral luminosity to magnetic moment. [The interpretation of IUE data to obtain total auroral luminosity is itself subject to considerable uncertainty (*10*), but this uncertainty will become increasingly negligible as the present IUE observations are supplanted by further IUE and Voyager ultraviolet spectrometer (UVS) observations.] With due regard for these uncertainties, we estimate the various relevant efficiency factors as follows.

In the case of Earth's magnetosphere, the total available power is $P_E/\epsilon_E \simeq 8 \times 10^{12}$ W (obtained from Eqs. 1 to 3, with ρ = 5 amu/cm^3, v = 400 km/sec, and $R_m = 10\ R_E$), and a fraction $\epsilon_{E1} \simeq 0.025$ of this available power is evidently extracted by the magnetosphere (*11*). A further fraction $\epsilon_{E2} \simeq 0.1$ is evidently converted by the magnetosphere into a precipitating electron energy flux; this fraction can be estimated, for example, from the ratio of the typical magnetic field–aligned voltage drop to the typical cross-magnetosphere voltage drop (*4*). The product of these two efficiency factors (0.0025) is consistent with the estimated global rate of energy precipitation in electron auroras [$\sim 2 \times 10^{10}$ W (*12*)]. The Lyα conversion efficiency ϵ_{E3} depends on atmospheric composition and structure as well as on the composition and energy distribution of the precipitating auroral primary particles; a plausible value for the Uranus atmosphere is $\epsilon_{E3} \simeq 0.04$ (*13*). The overall efficiency factor for an Earth-like system is thus estimated as

$$\epsilon_E \simeq 10^{-4} \quad (12)$$

Because each of the three efficiency factors is uncertain by perhaps a factor of 2, ϵ_E has an uncertainty of nearly ± 1 in the exponent.

In the disk-dynamo interaction, the theory provides an explicit expression of the efficiency of extraction ϵ_{d1} of planetary rotational energy:

$$\epsilon_{d1} = g(\sigma) \quad (13)$$

where $g(\sigma)$ is an algebraic function [equation 46 in (*4*)] of the parameter

$$\sigma = \mu_0 v \Sigma \approx \Sigma/(2 \text{ mho}) \quad (14)$$

where Σ is the height-integrated Pedersen conductivity of the polar cap ionosphere. The function $g(\sigma)$ varies between the limiting values $g(0) = 0$ and $g(\infty) = 1$, with a most likely intermediate value $g(1) = 2/9 \approx 0.2$. Lacking evidence to the contrary, we assume that the other two efficiency factors are the same for the disk-dynamo interaction as for the Earth-like interaction ($\epsilon_{d2} \simeq 0.01$ and $\epsilon_{d3} \simeq 0.04$); the overall efficiency for the disk-dynamo interaction is thus estimated as

$$\epsilon_d \simeq 10^{-3} \quad (15)$$

with (again) an uncertainty of nearly ± 1 in the exponent. Combining Eqs. 15 and 12 with Eqs. 5 and 4, respectively, we obtain our present best estimate of the auroral UV power output that would result from the disk-dynamo and Earth-like mechanisms:

$$P_d \simeq (1.8 \times 10^9 \text{ W})\ (M/M_B)^{4/3} \quad (16)$$

$$P_E \simeq (1.5 \times 10^9 \text{ W})\ (M/M_B)^{2/3} \quad (17)$$

where v = 400 km/sec, $\rho = 1.4 \times 10^{-2}$ amu/cm^3 (corresponding to 5 amu/cm^3 at 1 AU), $\Omega = 1.1 \times 10^{-4}$ rad/sec (*9*), and we have normalized the magnetic moment by the Blackett's law value $M_B = 1.7\ GR_U^3$, which is widely regarded as most plausible. The large uncertainty in the efficiency factors is reflected in these power estimates. As we noted earlier, the dependence on magnetic moment is different for the two mechanisms, but the estimated power output for the Blackett's law value of the magnetic moment is (by coincidence) about the same for the two mechanisms.

By inverting Eqs. 16 and 17 we obtain the expressions whereby the value of the magnetic moment can, in principle, be inferred from the remotely observed auroral emission power:

$$M_d \simeq (4\ GR_U^3)\ (P_{UV}/5.8 \times 10^9 \text{ W})^{3/4} \quad (18)$$

for the disk-dynamo mechanism, and

$$M_E \simeq (13\ GR_U^3)\ (P_{UV}/5.8 \times 10^9 \text{ W})^{3/2} \quad (19)$$

for the Earth-like mechanism. In these expressions P_{UV} represents the total power radiated in auroral emissions, and it is normalized to the value 5.8×10^9 W that is presently inferred from the IUE observations (*14*). If we regard each of the separate efficiency factors as uncertain within a factor of 2, then the uncertainty of the overall efficiency is a factor of 8, and the resultant uncertainty in the magnetic moment required for a given auroral luminosity is a factor of $(8)^{3/4} \approx 5$ in Eq. 18 or a factor of $(8)^{3/2} \approx 23$ in Eq. 19. Thus the value $4\ GR_U^3$ in Eq. 18

represents a possible range 0.8 to 20 GR_U^3 and the value of 13 GR_U^3 in Eq. 19 represents a possible range 0.6 to 300 GR_U^3.

In Fig. 1 the values that we would infer for the magnetic moment of Uranus are plotted as a function of the time at which the planet is first detected remotely during the Voyager encounter by the UVS and planetary radio astronomy (PRA) instruments. In both the disk-dynamo interaction model (Fig. 1A) and the Earth-like interaction model (Fig. 1B) the three continuous lines show, for a given date of first detection by the UVS instrument, the upper and lower limits and the intermediate "most likely" value of the corresponding magnetic moment as inferred from the above analysis. The most likely values in Fig. 1, A and B, are obtained from Eqs. 18 and 19, respectively, while the upper and lower limits are larger and smaller by factors of 5 and 23, respectively, in accordance with the above discussion. For comparison, the dashed curves in each panel illustrate the radiometric Bode's law function, proposed by Desch and Kaiser (*6*), whereby the low-frequency radio emission consumes a fixed fraction ϵ_r of the total solar wind power incident on the magnetosphere. In Fig. 1B the two dashed curves represent precisely the radiometric Bode's law of Desch and Kaiser, with the two extreme values $\epsilon_r = 3.6 \times 10^{-6}$ and $\epsilon_r = 6.2 \times 10^{-6}$ as inferred by them from their analysis of solar wind–controlled radio emissions from Earth, Jupiter, and Saturn. In Fig. 1A the two dashed curves represent the analogous scaling law that would apply to the disk-dynamo model, with the maximum available power given by Eq. 9 rather than Eq. 8. We have assumed that the overall radiometric conversion efficiency (both upper and lower limits) is the same for the disk-dynamo and Earth-like interactions, because the disk-dynamo interaction is probably the source of the radio emissions from Jupiter and Saturn (*15*). There is additional uncertainty in the interpretation of the radio emissions because of possible differences in beaming geometry between the planets.

In generating Fig. 1 we translated the independent variable from power output (UV or radio) to the time of marginal detection by the relevant Voyager instrument; this translation obviously requires an assumption as to the sensitivity of the two instruments in terms of the energy flux required for marginal detection of planetary emissions above background. We have adopted marginal detectable energy fluxes of 1.00×10^{-13} W/m^2 for the UVS instrument and 3.14×10^{-17} W/m^2 for the PRA instrument; Sandel (*16*) and Kaiser (*17*) provided the essential information on which these estimates are based.

Also indicated in Fig. 1 are the values of the magnetic moment corresponding to Blackett's law and the range of values for the magnetic moment that would be consistent with the radiative power output presently inferred (*14*) from the IUE observations.

If the magnetic moment has the Blackett's law value, then the radiometric Bode's law predicts that radio emissions should first be detected in September or October 1985 for the disk-dynamo model or between January and April 1985 for the Earth-like model, while both models would anticipate first detection of auroral emissions between November 1985 and mid-January 1986. On the other hand, if we adopt the best-guess value for the magnetic moment that would be required to produce the auroral power output inferred from the IUE observations (~4 GR_U^3 for the disk-dynamo model or ~13 GR_U^3 for the Earth-like model), then we find that the expected time for first detection of radio emissions by the PRA instrument has already passed in the case of the Earth-like model (*6*), and moves to June through August 1985 for the disk-dynamo model; for either model the first detection of auroral emissions by the UVS instrument would be expected around 1 December 1985. A wide range of first detection times can be accommodated by suitable choice of magnetic moment; once the magnetic moment is determined in situ, however, it should be possible to distinguish between the two interaction models and to better determine the relevant power conversion factor.

It may even be possible to distinguish between the two interaction models before the Voyager encounter with Uranus by correlating the observed UV power output with the incident solar wind parameters. Although the contrast between the two models is more pronounced in their dependence on solar wind velocity than in their dependence on solar wind density (Eqs. 4 and 5), density may be the more useful parameter because it is intrinsically more variable than velocity in the outer solar system (*18*).

The morphology of the auroral emission regions, as observed by the UVS

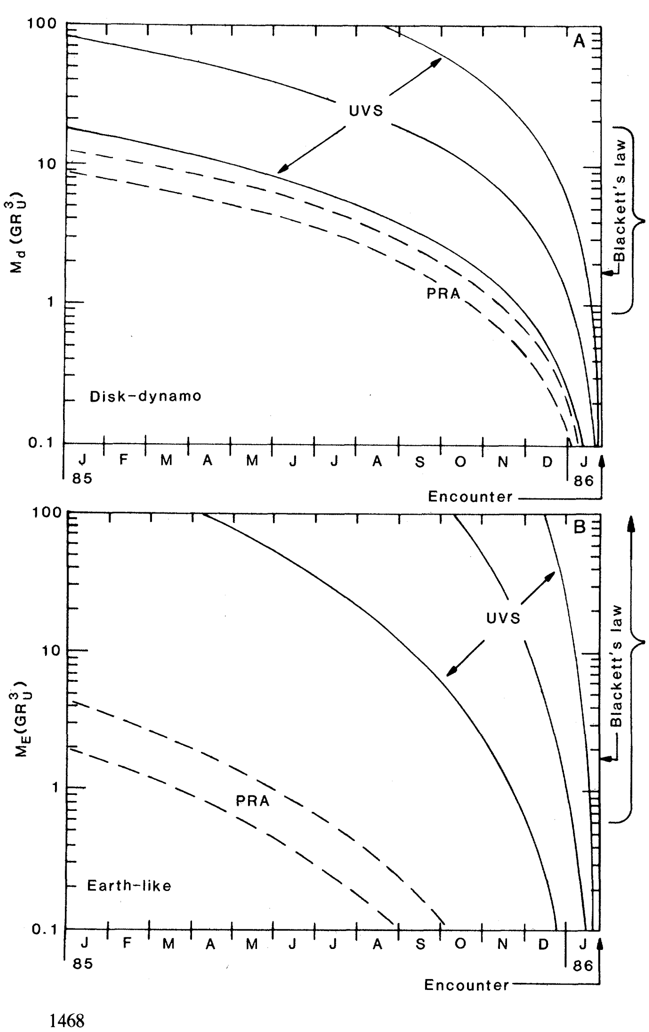

Fig. 1. Values of the magnetic moment of Uranus as required by the disk-dynamo model (A) and by the Earth-like interaction model (B) to account for given times of marginal detection of planetary emissions during the approach of Voyager. The three continuous curves show upper and lower limits and the intermediate best-guess value for the magnetic moment corresponding to a given date of first detection of auroral Lyα emission by the UVS instrument. The two dashed curves show the range of magnetic moments allowed by the radiometric Bode's law (*6*) for a given date of first detection of radio emissions by the PRA instrument.

instrument before and after the Uranus encounter, may also provide evidence for or against the disk-dynamo interaction model. This model predicts (*4*) that the nightside aurora, if any, should be dimmer than the dayside aurora, and that the morphology of the dayside auroral emission region should depend on the orientation of the magnetic dipole moment relative to the solar wind, forming a bright circular ring at the polar cap boundary if the north magnetic pole faces the sun or a diffuse glow filling the center of the polar cap if the south magnetic pole faces the sun. No such predictions are available for an Earth-like interaction model within the expected pole-on geometry.

If the observations of bright Lyα radiation from Uranus are being interpreted correctly as indicating a polar aurora (*1–3*), the aurora is a powerful one. According to either of the theoretical models described herein, the inferred auroral emission output of at least 6×10^9 W (*14*) implies a large magnetosphere, which in turn implies a large planetary magnetic moment. It is apparent that remote sensing of auroral emissions does not provide a precise determination of a planetary magnetic moment because of the uncertainties in the various mechanisms involved and their efficiencies. However, reasonable lower limits can already be established that indicate that Uranus has a significant dipole moment.

If we accept the present interpretation of the IUE observations of Uranus (*1–3*), then the surface magnetic field of Uranus must have a value of at least 0.6 G, making it the second strongest magnetic field of any of the planets. At this lower limit the magnetosphere, operating at maximum efficiency, is just large enough to collect enough power from the solar wind to drive the aurora. The most probable value of the surface magnetic field, again based on the IUE results, is ~4 G according to the disk-dynamo model and ~13 G according to the Earth-like model. The upper limits range from 20 to 300 G and are hardly to be taken seriously. During the next few months Voyager approach observations should allow us to sharpen our estimates; in early 1986 Voyager will test our theoretical understanding by direct measurements in situ.

T. W. HILL
Center for Space Physics, Rice University, Houston, Texas 77251
A. J. DESSLER
Space Science Laboratory, NASA Marshall Space Flight Center, Huntsville, Alabama 35812

References and Notes

1. J. T. Clarke, *Astrophys. J.* **263**, L105 (1982).
2. S. T. Durrance and H. W. Moos, *Nature (London)* **299**, 428 (1982).
3. J. Caldwell, R. Wagener, T. Owen, M. Combes, T. Encrenaz, *ibid.* **303**, 310 (1983).
4. T. W. Hill, A. J. Dessler, M. E. Rassbach, *Planet. Space Sci.* **31**, 1187 (1983).
5. T. D. Carr, M. D. Desch, J. K. Alexander, in *Physics of the Jovian Magnetosphere*, A. J. Dessler, Ed. (Cambridge Univ. Press, New York, 1983), p. 226.
6. M. D. Desch and M. L. Kaiser, *Nature (London)* **310**, 755 (1984).
7. T. W. Hill and F. C. Michel, *Rev. Geophys. Space Phys.* **13**, 967 (1975).
8. P. M. S. Blackett, *Nature (London)* **159**, 658 (1947).
9. R. A. Brown and R. M. Goody, *Astrophys. J.* **235**, 1066 (1980).
10. S. K. Atreya, private communication.
11. T. W. Hill, in *Solar-Terrestrial Physics*, R. L. Carovillano and J. M. Forbes, Eds. (Reidel, Dordrecht, Netherlands, 1983), p. 261.
12. R. D. Sharp and R. G. Johnson, *J. Geophys. Res.* **73**, 969 (1968).
13. J. H. Waite, Jr., private communication.
14. S. K. Atreya, private communication; J. T. Clarke, private communication.
15. J. Isbell, A. J. Dessler, J. H. Waite, Jr., *J. Geophys. Res.* **89**, 10,716 (1984).
16. B. R. Sandel, private communication.
17. M. L. Kaiser, private communication.
18. J. W. Belcher, private communication.
19. We thank J. T. Clarke, M. L. Kaiser, and B. R. Sandel for helpful discussions. The work at Rice University was supported by grant ATM83-11146 from the National Science Foundation.

23 November 1984; accepted 4 January 1985

Margin to Craton Expansion of Late Ordovician Benthic Marine Invertebrates

Abstract. *A biostratigraphic survey of 57 Late Ordovician marine shelly invertebrates from the* Climacograptus manitoulinensis *zone of eastern Canada supports suggestions that throughout the Early Phanerozoic benthic marine speciations occurred preferentially in marginal marine environments. The species subsequently spread onto the craton. There is no obvious positive correlation between the times of first appearance of new associations or novel communities along the continental margin and the first appearance on the craton of the species making up these communities. Taxonomic similarities between marine communities that occupied both marginal and cratonic regimes may reflect a more static local ecology than the evolutionary dynamics of a piecemeal species-by-species reassembly.*

The suggestion that many Paleozoic benthic marine invertebrates expanded from nearshore marginal marine environments into the cratonic offshore seas is the subject of this investigation. Eldredge (*1*) especially recognized the implications of such movement with regard to modes of speciation. Allopatric speciation was more likely to have taken place along the more spatially heterogeneous marginal environments. In many studies of faunal migrations the offshore, as compared to the marginal nearshore, environments usually have referred to bathymetrically deeper waters. Reconstructed shelf profiles then often resemble the present, passive Atlantic margin (*2*). Eldredge, however, defined the offshore as the epicontinental or epeiric sea regimes—that is, those marine environments that covered the continents during much of the Paleozoic and that seemingly lacked the degree of spatial heterogeneity characteristic of more marginal habitats.

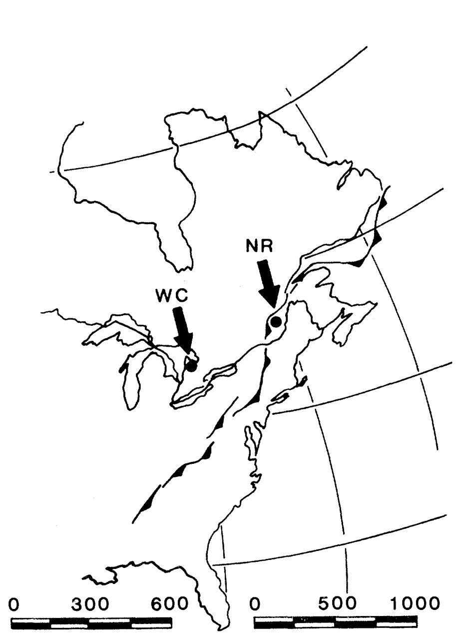

Fig. 1. Locality map of eastern North America showing the location of the Workman's Creek (WC), which is also known as the East Meaford Creek, and the Nicolet River (NR) exposure (*8*). The heavier barbed line indicates the edge of the thrust belt or highly folded strata.

The details of multispecies expansion have been clouded by biostratigraphic imprecision especially in correlation between localities in different geological provinces (*3*). Correlations often must be carried out through the use of temporally persistent species, and although accurate, faunal zones can span millions of years. In the case of the Ordovician the most reliable zones used to correlate