where h_T is the height of the tropopause and X is a correction to the total cross section $\sigma(r)$ when particle diameters are comparable with wavelengths of light. For consideration of the extinction of visible light, it is reasonable to let X equal $r/(2 \times 10^{-4})$ for $r < 2 \times 10^{-4}$ cm; otherwise X equals 1 (*10*). Earlier computations (*11*) for $v(r, h)$ on Mars were adapted to the atmosphere of Venus. An atmospheric model (*12*) was used, with surface temperatures of 620° to 720°K and surface atmospheric densities of 0.0174 to 0.150 g/cm^3. Typical values of $v(r, h)$ at 50 km were 0.0074 cm/sec for particles 1 μ in diameter, 0.66 cm/sec for 10-μ diameter, and 5.1 cm/sec for 100-μ diameter. The velocity of descent of very small particles is roughly proportional to the diameter squared. The particles were assumed to ascend to a tropopause altitude (h_T) of 60 km. The calculation of $v(r, h)$ is not valid for extremely small particles, so the integration of τ was cut off at $r \leqslant 2 \times 10^{-5}$ cm $= 0.2$ μ. Numerical integration of the optical depth yields the result $\tau \approx 2.7 \times 10^6 \cdot S$ for a mean atmosphere; this result is quite insensitive to the choice of atmospheric parameters.

It is apparent that τ is of the order unity for $S \approx 3 \times 10^{-7}$ sec^{-1}, about ten explosive eruptions per annum or 10 km^3 of material annually injected into the atmosphere. This rate of volcanic activity is considerably higher than the current rate on Earth if only the most violent eruptions carry large amounts of material as high as the tropopause. Nonetheless it does not seem unreasonable to us that Venus should sustain a rate of volcanic activity sufficient to keep the optical depth of suspended dust greater than unity. Our conjectural atmosphere would therefore contain high clouds of H_2O vapor and ice, and other volcanic gases, surmounting an optically thick suspension of fine dust particles. The dust particles might not be readily detectable from above, but would have profound effects on the dynamics of the lower atmosphere.

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7 April 1967

Radio Reflection by Free Radicals in Earth's Atmosphere

Abstract. *Reflections of megacycle-per-second radio signals by free radicals in Earth's ionosphere are observed having about the intensity predicted for induced magnetic-dipole transitions. It seems that magnetic atoms, ions, and molecules in planetary atmospheres may be detected by this method. These observations were made with the topside ionosonder of the Canadian satellite Alouette II.*

We report probable observation of the reflection by free radicals in Earth's upper Antarctic atmosphere of megacycle-per-second radiation. The measurements were obtained with the topside ionosonde satellite Alouette II; records from the south polar station were used because they were exceptionally clear. The satellite (*1*), lofted into a nearly polar orbit with apogee at 3000 km and perigee at 500 km, remains well above the main part of the ionosphere.

Basically our point is that such radiofrequency sounding is an important technique for analysis of the upper atmosphere. The probability of spontaneous emission of magnetic-dipole emission at megacycle frequencies is very low, so that only absorption and induced emission are important. We calculate that by using the Alouette ionosonde one should be able to detect induced magnetic-dipole radiation from free radicals at concentrations as low as approximately 10^4/cm^3 (see *2*).

The signals we report, of frequencies lower than the electron gyrofrequency, have not been previously identified; we suggest that they are from magnetic-dipole transitions induced by the topside sounder pulse—transitions within a Zeeman multiplet split by Earth's magnetic field.

Our investigation stemmed from previous studies of the strange triggering action of the Jovian moon Io on the decameter radiation from Jupiter. Recently two of us suggested (*3*) that Io, orbiting in a Van Allen belt, produces energetic hydromagnetic disturbances in the Jovian magnetic field, which propagate by Alfven-wave transport into the Jovian ionosphere below. Free radicals, expected to be abundant in Jupiter's reducing atmosphere, transduce this perturbing energy in a manner similar to reflection, the energy being emitted as the decameter radio signal.

The ionosonder in Alouette II is a transmitter and receiver which simultaneously sweeps from 0.2 to 14.5 Mc/sec during each 30-second interval. At the beginning of each interval the transmitter emits a 100-μsec pulse at a frequency of 0.2 Mc/sec and an average power of 300 watts. After a 2-μsec delay, there follows a receiving period of 33 msec; then the transmitter emits a second pulse of higher frequency, followed by another listening period, and so on.

This sequence is repeated 900 times during the 30-second interval as the frequency increases from 0.2 to 14.5 Mc/sec, the pulse length and power and the receiving period remaining constant. For each interval an ionogram displays the frequency of any detected signal, its time of arrival, its intensity, and the real time. For the ionogram records now reported, the signal intensities were not available.

Figure 1 shows a series of consecutive 30-second ionograms, with examples of signals that we attribute to induced magnetic-dipole radiation from free radicals. Figure 2 shows a distribution of Landé g values calculated from some 500 signals found by examination of more than 100 ionograms; the values were computed from the frequency of each signal divided by the local geomagnetic field ($g = 0.714$ ν/B). The field at the satellite was computed from a polynomial expansion of the geomagnetic field; values so computed

Table 1. Landé g values for ground and metastable states of atomic and molecular species in Earth's atmosphere.

g Value	Free radical	State	
0.71–0.74	OH	Ground	$^2\Pi_{3/2}$
0.76–0.79	NO	Ground	$^2\Pi_{3/2}$
0.79	OH	Ground	$^2\Pi_{3/2}$
0.80	N I	Metastable	$^2D_{3/2}$
0.80	O II	Metastable	$^2D_{3/2}$
1.00	N II	Metastable	$^1D_2$
1.00	O I	Metastable	$^1D_2$
1.20	N I	Metastable	$^2D_{5/2}$
1.20	O II	Metastable	$^2D_{5/2}$
1.33	N I	Metastable	$^2P_{3/2}$
1.33	O II	Metastable	$^2P_{3/2}$
1.45	OH	Ground	$^2\Pi_{3/2}$
1.50	N II	Metastable	$^3P_2$
1.50	O I	Ground	$^3P_2$

agree within 1 percent with values computed from the electron gyrofrequency and its harmonics as shown on the ionograms.

Probable magnetic-dipole reflections are indicated by peaks in the g-value distribution of Fig. 2. Appropriate g values are labeled by the states of atomic oxygen and nitrogen and molecular OH and NO that appear to fit. Table 1 contains a list of likely free radicals, with their g values.

Transitions having g values less than 0.6 and greater than about 1.8 have not been measured because of ionogram noise at lower frequencies and the broad cyclotron and plasma and hybrid signals at higher frequencies. For species showing $g = 2.0$ (for example, ground states of H I, He II, N I), detection is hampered because the magnetic-dipole signal coincides with the electron gyrofrequency.

The sources of the peaks at g values of 0.93 and 1.68 to 1.76 have not been identified. In general, g values have been measured in the laboratory for very few gaseous atomic species and even fewer gaseous diatomic species (*4*). In making these identifications we have used theoretically calculated g values for atomic species (*5*), and experimental g values for the diatomic species (*6*).

In this method of analysis, ambiguities arise for monatomic species:

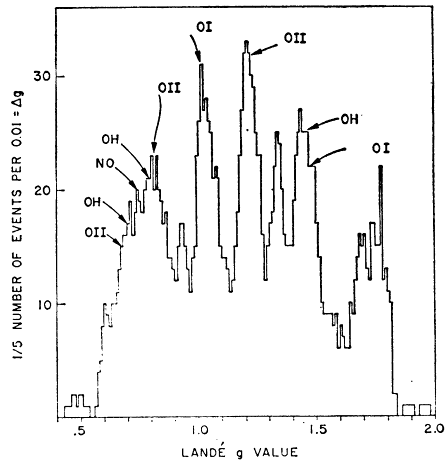

Fig. 2. Distribution of g values for about 500 signals taken from over 100 ionograms recorded in Antarctica. Peaks in the distribution are believed to be reflections from free radicals. The labels indicate possible assignments of free radicals. (We believe that the peak at 1.50 may have been somewhat shifted as a result of determinable errors in the fiducial ionogram markers.)

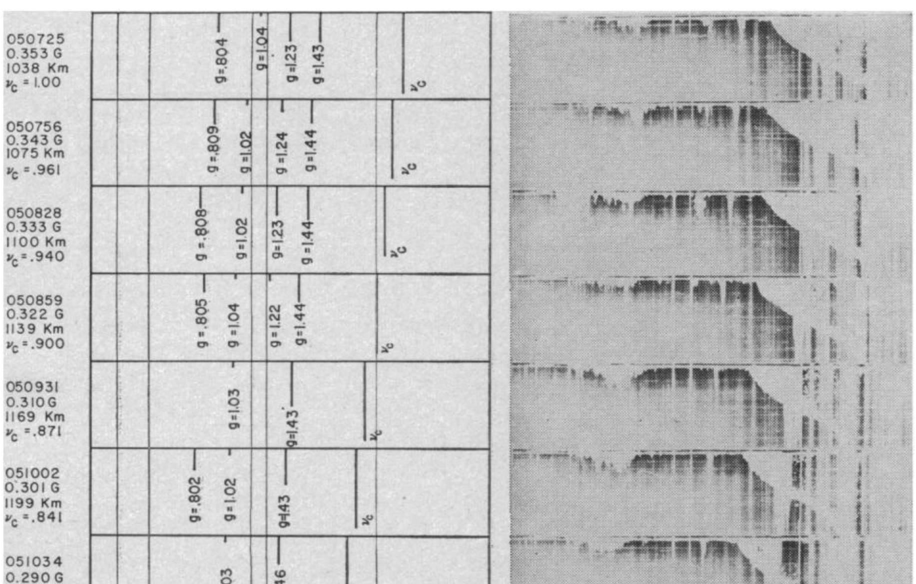

Fig. 1. Ionograms from the Alouette II topside ionosonde, taken over Antarctica and showing signals thought to be caused by magnetic-dipole transitions induced by free radicals. The cyclotron frequency of free electrons (right) is seen to move with changing local magnetic field, and the free radical signals move in the same way. The gyromagnetic ratios, g values, for the several signals are shown on the left of the ionograms. The legend on each ionogram indicates universal time (6-digit number), on day 029 of 1966, local magnetic field in gauss, altitude in kilometers, and electron cyclotron frequency ν_c in megacycles per second.

for example, nitrogen and oxygen, and even neon (*7*), show similar ground and metastable states—N I (^4S, ^2P, ^2D), N II (^3P, ^1D), N III (^2P), O I (^3P, ^1D), O II (^4S, ^2P, ^2D), O III (^3P, ^1D)—and the g values will be common insofar as these species behave according to the theory.

For diatomic species the g values may very well be distinctive but numerous, for the effect of the molecular vibration and rotation produces different g values in each fine-structure state. These values cannot be calculated with certainty and very few have been measured (*4*). Oxygen is an exception. For molecular oxygen (*8*) the g values are known to be 0.5 and smaller, so that emission in this instance would occur at frequencies near the lower edge of the range of our observations.

Considering the local electron densities to be about $10^5/cm^3$, as indicated by plasma frequency reflection (*9*) on the ionograms (see, for example, Fig. 1), it may be that Earth's upper ionosphere provides an excellent laboratory for measurement of g values.

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2. With the magnetic-dipole moment μ of about 10^{-20} erg/gauss, we expect approximate equality of the concentrations, of a particular species, with dipoles parallel and antiparallel to the local magnetic field, both equalling $N/2$—half the total concentration. For the particles indicated by the Alouette signal, the probability of reemission, equal to the probability of absorption, in terms of the Einstein coefficient for stimulated emission, is

$$W = [2\pi(\mu^2/3)/\hbar^2 c](dI/d\nu) = 2 \times 10^4\,(dI/d\nu)\ \text{sec}^{-1}$$

where $dI/d\nu$ is the energy flux from the sounder-transmitter per unit frequency interval. The average radiated power, 300 watts, is spread over a bandwidth of about 30 kcs. If one neglects absorption between the satellite and a point at distance R, the energy flux at R is

$$dI/d\nu = 10^5/4\pi R^2\ [\text{erg/cm}^2\ \text{sec (cy/sec)}]$$

We neglect the angular dependence and assume that the power reflected by a population of N magnetic dipoles per cubic centimeter, given by

$$P(R) = W\ (N/2)\ h\nu = 0.5 \times 10^9\,(N/2)\,h\nu/4\pi R^2\ (\text{erg/cm}^3\ \text{sec})$$

is radiated isotropically. It is assumed that the radiated power density is approximately constant over the line width of the effective radicals. The intensity of the signal arriving at the satellite at time t, measured from the time at which the 100-μsec transmitter pulse begins, is given by

$$S(t) = \int [P(R)/4\pi R^2]\ dV\ (\text{erg/cm}^2\ \text{sec})$$

where the integral is taken over the volume of origin of reemitted radiation reaching the satellite at time t. This volume is a spherical shell centered on the satellite. For a pulse of 100 μsec, the inner surface of the shell has radius $R_1 = c(t - 100)/2$, and the outer surface has radius $R_2 = ct/2$, where t is measured in microseconds. By integration over the spherical angular coordinates and use of $\nu = 10^6$ cy/sec, it follows that

$$S(t) = \int_{R_1}^{R_2} P\ dR = 1.5 \cdot 10^{-13}\,N \int_{R_1}^{R_2} dR/R^2$$

If the signal is to be detected at the satellite, $S(t)$ must be greater than the threshold of the receiver, that is, $S(t) \geqq 3 \times 10^{-15}$ erg/cm^2 sec. Furthermore the signal must be at least 100-μsec long, that is, $t = 202$ μsec. For the minimum value of detectable signal, therefore,

$$\int_{R_1}^{R_2} dR/R^2 = 6 \times 10^{-7} \text{ and}$$

$$N \geqq 3 \cdot 10^4\ \text{cm}^{-3}$$

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10. Work aided by NASA grant 237-62, contract 249-62. We thank G. L. Nelms, T. R. Hartz (both of the Canadian Defense Research Telecommunications Establishment), and W. Calvert (U.S. National Bureau of Standards) for advice and information regarding the Alouette instrument; C. Sonett, L. Colin, and K. L. Chan (Ames Research Center) for lending the south polar records of Alouette II; D. Stork (University of California, Los Angeles) for use of film-measuring equipment; and M. Mizushima (University of Colorado) for discussions of the magnetic properties of molecular oxygen.

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16 May 1967

Geostrophic Transport Through the Drake Passage

Abstract. *Geostrophic velocity and transport of water in the Drake Passage relative to a newly defined zero reference layer indicate that the circumpolar current is basically north of 59°S, with its axis north 57°S, and that the total volume transport exceeds 200 × 10⁶ cubic meters per second. The calculated geostrophic velocities are consistent with results of descriptive water-structure studies.*

Estimates of the total volume transport through the Drake Passage vary from 0 (*1*) to 165 × 10^6 m^3/sec (*2*). The uncertainty arises from a lack of direct current measurements and an inability to define a satisfactory reference layer. The reference layer is needed to convert relative geostrophic velocities into absolute values. For this purpose, the level of no motion or the zero reference layer is generally used. It can be found by various methods (*3*).

In general, velocity decreases with depth; therefore, any deep isobaric surface would suffice as a zero reference layer for the determination of surface currents. However, the depth of the zero reference layer becomes critical for calculations of deep currents and total volume transport.

Table 1 summarizes the past estimates of the total volume transport through the Drake Passage. The transport values vary with changes of the reference layer, even though, in many cases, the same hydrographic data are used.

The zero reference layer in the southern Drake Passage (*4*) is used to determine the mean density of overlying water. The reference layer may then be extended northward by use of the equivalent-barotropic assumption (*5*). This assumption has yielded meaningful results in stratified water (*5*) and may be of use in water of a homogeneous nature such as that found in the Antarctic Ocean. The assumption was applied to the Drake Passage by Ostapoff (*1, 6*); however, the initial zero reference layer was found by extrapolation of Defant's Atlantic Ocean reference layer (*7*) into the Drake Passage. Ostapoff's resulting velocities show a westward-flowing deep and bottom current. This calculation does not agree with the descriptive analysis of the hydrographic data which indicates that the bottom flow of the northern Drake Passage is rapid and toward the east, and that no zero reference layer exists within the water column of the northern Drake Passage (*4, 8*).

The hydrographic stations for which geostrophic calculations were performed are plotted in Fig. 1. The calculated velocities are perpendicular to the

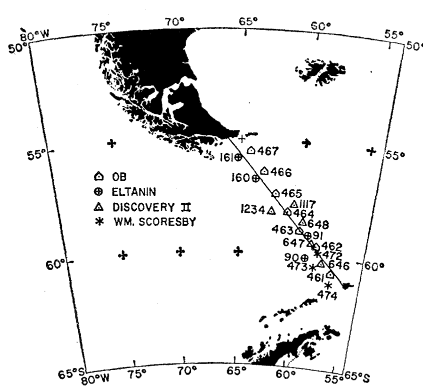

Fig. 1. Hydrographic stations used in geostrophic calculations.

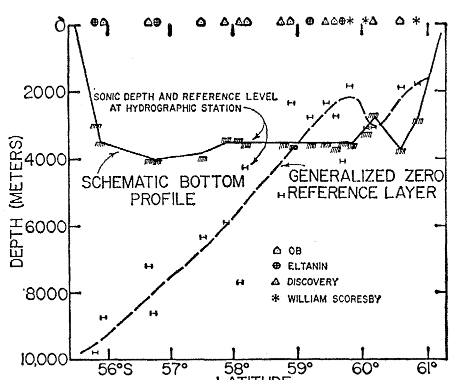

Fig. 2. Depth of zero reference layer in the Drake Passage.