POSSIBILITY OF DETECTING METEORITES BURIED WITHIN THE ICE BY RADIO ECHO SOUNDING

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***Abstract*:** Recovery of large numbers of Yamato meteorites and Allan Hills meteorites in Antarctica led us to postulate the presence of meteorite pieces still buried in the ice. To elucidate the concentration mechanism of a large number of meteorites within a limited region in the bare ice areas, it may be significant if meteorites buried within the ice could be detected. If meteorites buried in the ice are taken out together with the surrounding ice, valuable information on chronological problems of both meteorite and ice will be obtained.

A theoretical analysis on the possibility of locating of meteorites buried in the ice by means of radio echo sounding is described in this paper. The radar equation is used to calculate the reflected power from meteorite pieces buried in ice. Assuming that meteorite pieces are spherical in shape and iron meteorites are conductive spheres, we may investigate the problem of the case where reflections from meteorite pieces within the ice are strong enough to be detected with the radio echo sounding apparatus applying the electromagnetic wave of 400 MHz and 80 MHz, taking $G_0=2$ as the antenna gain, and $P_r/P_t=10^{-10}$ as the ratio of the received and transmitted power.

As the size distributions of diameter of meteorite pieces are given for the Yamato stony meteorites and the iron meteorites, the relation between the detectable diameter of meteorite pieces and the burial depth in the ice was obtained. It was concluded that the Yamato stony meteorites may be detectable unless the burial depth exceeds 10 m. However, most of the Yamato stony meteorites having the maximum frequency of diameter of about 1 cm are probably detectable if they are buried within a depth of 1 m. For the iron meteorites, if the diameter is about 20 cm, the maximum frequency of diameter in size distribution, they are detectable within the depth of about 50 m.

1. Introduction

During the 1977–1978 field season, the U.S.-Japan joint party found 303 meteorite pieces on the bare ice surface near the Allan Hills (76°45′S, 159°30′E) in Victoria Land, Antarctica (YANAI, 1979). Since that season, about 650 specimens have been found and collected in a small bare ice field of about 50 km^2 in area.

NAGATA (1978) proposed a possible mechanism of concentration of meteorite pieces, assuming that a large number of meteorites which fell over the Antarctic ice field during a long period of time and were buried deeply in the ice have been transported by the ice sheet movements which result in a horizontal convergence and an upward movement of the ice flow due to the bedrock topography. Another necessary condition is the exposure of meteorites on the bare ice surface caused by the ablation effect.

It has been assumed, from the topographic situation near the Allan Hills, that meteorite pieces found on the bare ice surface might be conveyed by the ice masses coming up from the interior of the ice sheet and disclosed on the bare ice surface as the result of continuous ablation and scraping of ice. NISHIO and ANNEXSTAD (1980) observed the upward movements and the rate of ablation of ice on the bare ice surface and added significant data to ascertain the above assumption.

Since the meteorite pieces found on the bare ice surface near the Allan Hills were concentrated in a comparatively small area, it may be assumed that meteorites buried deeply in the interior of the Antarctic ice field are continuously conveyed by the ice flow and accumulated in the limited area of the bare ice surface, while many other meteorite pieces may be still remaining within the ice. This suggests that meteorite pieces remaining within the ice may probably be on their way to come out onto the bare ice surface.

If meteorites buried in the ice can be previously detected and taken out together with the surrounding ice, it becomes possible to date the ice surrounding the meteorites, by comparing with the terrestrial age of the meteorite determined by a measurement of the decay function of a radioactive element contained in the meteorite.

During the glaciological survey in the 1978–1979 field season (NISHIO and ANNEXSTAD, 1979), KOVACS (1980) has tried to locate meteorites buried within the ice in the bare ice area near the Allan Hills in Victoria Land, Antarctica, using a radio echo sounding with a pulse radar operated at a frequency of 250 MHz, but no buried meteorite fragments were detected in the ice, because the radio echo sounding measurements experienced severe noise troubles which were found to be related to poor fabrication and electrical component problems.

Although there may be many methods such as magnetic, resistivity, gravity prospecting and others for prospecting meteorite buried in the ice, the author believes that the radio echo sounding is the most practical detecting technique. This paper presents the possibility or capability of this technique for the detection of meteorites buried in the ice.

2. Power Reflected from Meteorites within the Ice

In order to detect meteorites buried in the ice by a radio echo sounding device, it is necessary to know the echo strength of electromagnetic wave reflected from the meteorites. For the purpose of calculating the power of echo reflected from the meteorite pieces within the ice, we assumed that meteorite pieces are spherical in shape, and that the dielectric constant of stony meteorite is equal to that of granite ($\varepsilon = 8.0$) and iron meteorite is a conductive sphere. For simplification, it is assumed that a small number of meteorite pieces are dispersed uniformly in the ice in the isolated form and the strengh of the electric field is not attenuated throughout the ice.

We have to consider three types of scattering mechanisms, namely Rayleigh, Mie and optical scattering, to calculate the power reflected from spherical meteorite pieces depending on the wavelength of the electromagnetic wave and the diameter of spherical meteorites.

2.1. Back scattering cross-section of spherical meteorites

Figure 1 shows the variation of three types of the back scattering cross-section as a function of the diameter of spherical meteorite (d) and the wavelength of pulse radar (λ). It is seen that the back scattering cross-section depends on the factor $\pi d/\lambda$. When the diameter (d) of meteorites dispersed in the ice is very much smaller than the wavelength (λ), the Rayleigh scattering occurs (Type I). If the diameter of meteorites is nearly equal to the wavelength, the Mie scattering takes place (Type II), and when diameter is greater than the wavelength, the optical scattering (Type III) predominates over other two types.

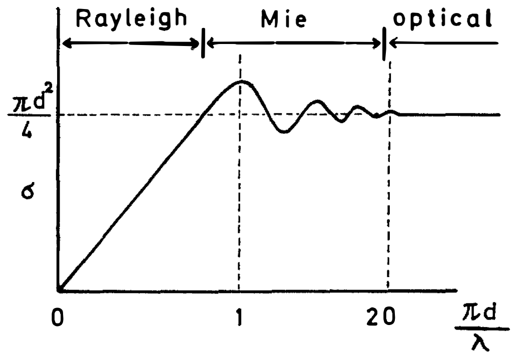

Fig. 1. A schema of the normalized back scattering cross-section of sphere (σ) depending on the factor $\pi d/\lambda$ as a function of diameter of spherical meteorite (d) and wavelength (λ) of electromagnetic wave of radio echo sounding apparatus.

Though the power of echo reflected from the spherical meteorite can be computed by using the radar equation to be given for the back scattering cross-section of each type of the scattering mechanism in the three cases as mentioned above, it is necessary to estimate previously the average diameter of meteorites dispersed in the ice. Bearing in mind the further search for the Antarctic meteorites buried in the ice, we shall examine the frequency distribution of the Yamato stony meteorites and the cataloged iron meteorites recovered in the past to estimate the mean diameter.

2.2. Size distribution of meteorite pieces

Figure 2 illustrates the frequency distribution of diameter of the Yamato stony meteorites and the cataloged iron meteorites (NAGATA, 1978). Since the shape of

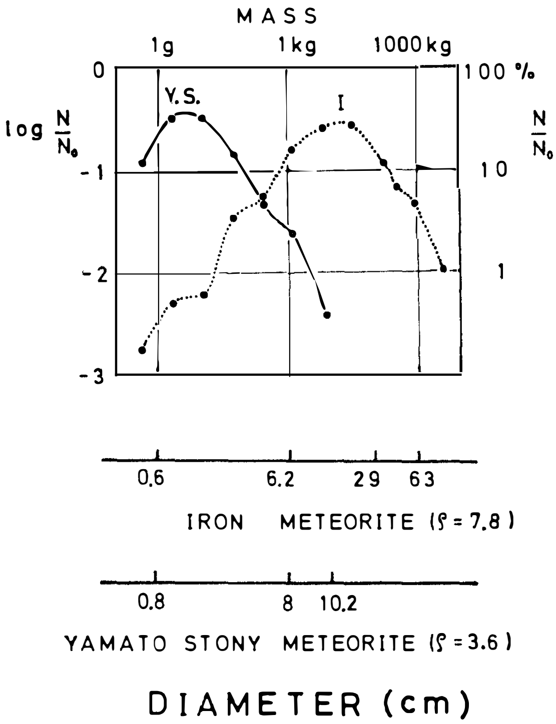

Fig. 2. Frequency spectrum of diameter of the Yamato stony meteorites (Y.S.) and the iron meteorites (I). Mass distribution of both Yamato stony meteorites and iron meteorites was given by T. NAGATA (1978).

meteorites was irregular, the diameter was calculated from the assumption that the density was 3.6 g/cm^3 for stony meteorite and 7.8 g/cm^3 for iron meteorite.

As seen in Fig. 2, the diameter at the maximum frequency was about 1 cm for the Yamato stony meteorites and about 20 cm for the cataloged iron meteorites, and the maximum value of diameter was about 10 cm and 70 cm, respectively.

When electromagnetic waves with frequency of 80 MHz (λ=210 cm in ice) and 400 MHz (λ=42 cm in ice) are respectively radiated into the ice, the Yamato stony meteorites will show the back scattering cross-section given by the Rayleigh scattering, since the value of factor $\pi d/\lambda$ is less than unity for the diameter smaller than about 10 cm at the maximum value.

However, the back scattering cross-section of the cataloged iron meteorites will be given by the Rayleigh scattering at the frequency of 80 MHz (λ=210 cm) for the diameter less than about 70 cm at the maximun value of diameter, but it will be given by the Rayleigh scattering and the Mie scattering at the frequency of 400 MHz (λ= 42 cm), because the value of $\pi d/\lambda$ at the maximum frequency of the cataloged iron meteorites is a little larger than unity.

2.3. *Calculation of the power reflected from spherical meteorites*

Under the assumptions mentioned in the foregoing subsection, the back-scattered power reflected from spherical meteorites may be given by applying the following radar equation:

$$\frac{P_r}{P_t}=\frac{G_0{}^2\lambda^2}{64\pi^3D^4}\sigma\,, \tag{1}$$

where P_r is the power reflected from spherical meteorite, P_t the transmitted power, G_0 the antenna gain, λ the wavelength of electromagnetic wave used, D the depth where the meteorite piece is buried in the ice, and the back scattering cross-section determined by the wavelength (λ) and the diameter (d) of spherical meteorite including the dielectric constant ($\varepsilon=8.0$) for stony meteorite.

Taking $G_0=2$ (the value of 3 in decibels) as the antenna gain and $P_r/P_t=10^{-10}$ (the value of -100 in decibels) as the maximum sensitivity of the back-scattered power received by the present radio echo sounding apparatus, we can derive inequalities (4) and (5) to solve the problem of detecting meteorite pieces buried in the ice from eq. (1) in the case of the Rayleigh scattering. In the case of the Rayleigh scattering, the back scattering cross-section (σ) is expressed in two ways:

$$\sigma=\pi^5\left|\frac{\varepsilon-1}{\varepsilon+2}\right|^2\frac{d^6}{\lambda^4} \qquad \text{for stony meteorite,} \tag{2}$$

$$\sigma=9\left(\frac{\pi d}{\lambda}\right)^4\left(\frac{\pi d}{4}\right)^2 \qquad \text{for iron meteorite as conductive sphere,} \tag{3}$$

where ε is the dielectric constant of the stony meteorite ($\varepsilon=8.0$) and d the diameter of the spherical meteorite. Substituting the back scattering cross-section in eqs. (2) and (3) into eq. (1) and assuming that whenever the maximun sensitivity of the back-scattered power is more than $P_r/P_t=10^{-10}$, we can obtain a criterion on the size of detectable meteorite pieces in the ice.

$$d^6\geqq C_0\lambda^2D^4 \qquad \text{for both stony and iron meteorites,} \tag{4}$$

where C_0 is the constant with respectively different values for the stony and iron meteorites.

The criterion given by inequality (4) indicates that the diameter is proportional to one-third of the wavelength of electromagnetic wave used in the radio echo sounding apparatus and two-thirds of the depth of ice.

Since most of the cataloged iron meteorites are larger in diameter than the Yamato stony meteorites as illustrated in Fig. 2, it may be expected that the iron meteorites show the Mie scattering rather than the Rayleigh scattering, but as the value of back scattering cross-section due to the Mie scattering fluctuates and converges rapidly into the value given by the optical scattering as seen in Fig. 1, the following criterion will be applied to the detectable diameter of iron meteorites.

$$d^2\geqq C_1D^4/\lambda^2\,, \tag{5}$$

where C_1 is the constant for the optical scattering with the back scattering cross-section as $\sigma=\pi d^2/4$.

The diameter of iron meteorite is proportional to the square of the depth of ice but is reciprocally proportional to the wavelength.

3. Possibility of Detecting Meteorites in the Ice

Figure 3 shows the criteria for detectable and undetectable meteorites as a function of diameter, depth and frequency of electromagnetic wave of 80 MHz and 400 MHz. In this figure, the detectable domains indicate that the intensity of echo reflected from the meteorite buried in the ice is sufficient to be detected by the present radio echo sounding apparatus taking $G_0=2$ as the antenna gain and $P_r/P_t=10^{-10}$ as the maximum sensitivity of the back-scattered power from spherical meteorite.

As shown in Fig. 3, the detectable domain for iron meteorite is larger than that for stony meteorite, suggesting that if the diameter is identical, the detectable depth for iron meteorite must be deeper than that for stony meteorite. The detectable domain extends to smaller diameter of meteorite and larger depth with using higher

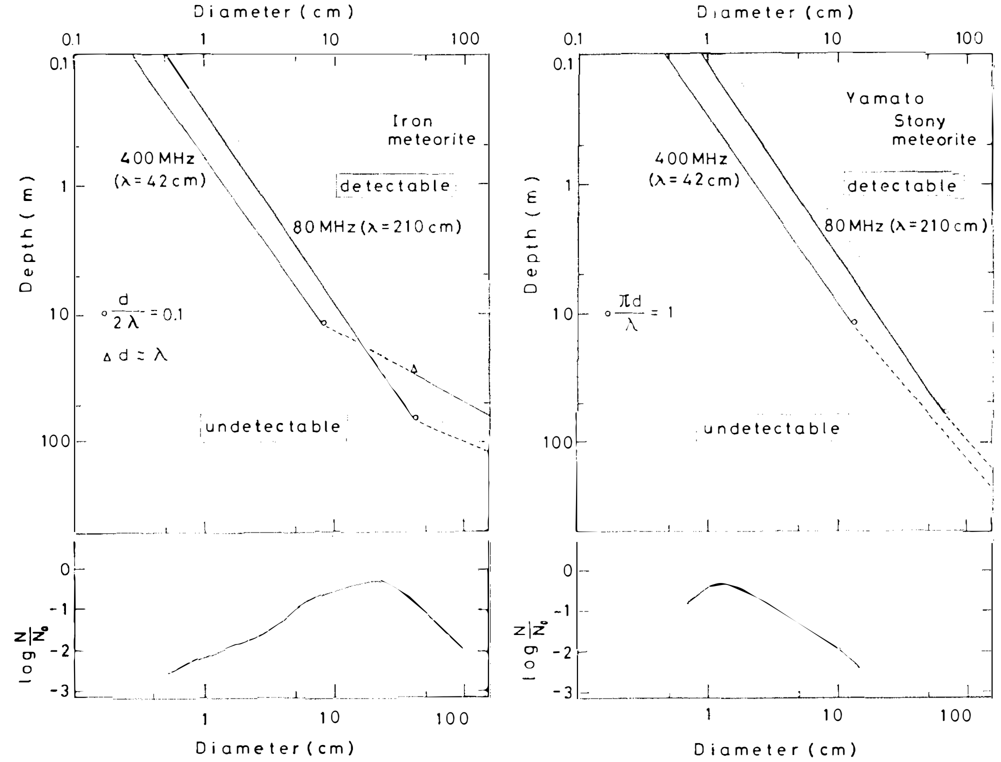

Fig. 3. Relation between the depth of ice and the diameter of spherical meteorite for the iron meteorites and the Yamato stony meteorites when electromagnetic wave having frequency of 80 MHz ($\lambda=210$ cm in ice) and 400 MHz ($\lambda=42$ cm in ice) are respectively radiated into the ice. In the lower part of the figure, the frequency spectrum of diameter of the Yamato stony meteorites is shown. The relation dependent on the Mie scattering is shown with the dashed line.

frequency, but it should be noted that for iron meteorite, the frequency dependence on the detectable domain becomes reciprocal at the diameter larger than about 10 cm where the scattering aspect due to meteorite pieces dispersed in the ice changes from the Rayleigh scattering into the Mie scattering and then into the optical scattering.

The maximum frequency of diameter of meteorites, which have been found and collected on the bare ice surface near the Allan Hills in Victoria Land and in the Meteorite Ice Field near the Yamato Mountains, Antarctica, was 20 cm for the iron meteorites and 1 cm for the stony meteorites as shown in Fig. 2. Since the frequency of electromagnetic waves of the present radio echo sounding apparatus was 80 MHz and 400 MHz, it may be clear that if stony meteorites having diameter of 1 cm exist at a depth of 10 m, they can not be detected unless their diameter exceeds about 20 cm. However, if the diameter of iron meteorite is about 100 cm, it may be detectable by the electromagnetic wave of 80 MHz even when the meteorite is buried at the depth of about 100 m.

4. Concluding Remarks

In the foregoing section, it has been shown that when the radar antenna happens to be pulled over meteorites buried in the ice, the meteorites can be detected by the conventional radio echo sounding apparatus, and that the criterion to determine whether the meteorite is detectable or not is given by three parameters such as the diameter of meteorite, the depth, and the frequency of the electromagnetic wave used. It is concluded that for the Yamato stony meteorites having the largest diameter of 20 cm in the size distribution curve, it may be possible to detect them unless the burial depth exceeds 10 m. However, the Yamato stony meteorites having the maximum frequency of diameter of about 1 cm in the size distribution curve are probably detectable if they are buried within 1 m in depth.

As given by inequality (4), since the detectable depth for meteorites is reciprocally proportional to the square-root of the wavelength, it is suggested that the meteorites are detectable by the use of the frequency 400 MHz (λ=42 cm in ice) rather than 80 MHz (λ=210 cm in ice). However, it should be noted that the amplitude of electromagnetic wave with higher frequency decreases very rapidly with depth.

For the iron meteorites, if the diameter is about 20 cm, the maximum frequency of diameter in size distribution, they are detectable down to the depth of about 50 m. When the electromagnetic wave of 400 MHz is used, the back scattering due to iron meteorites causes the Mie scattering and hence the relation between the detectable depth and the diameter should be calculated in more detail in the future.

As a high resolution radio echo sounding technique allows us to detect meteorites buried in the ice, it will be of great interest to undertake such a radio echo sounding to prospect meteorites in the area of the Meteorite Ice Field near the Yamato Mountains and in the bare ice areas near the Allan Hills in South Victoria Land, where hundreds of meteorites have been found resting on the glacial ice surface in recent years.

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References

KOVACS, A. (1980): Radio-echo sounding in the Allan Hills, Antarctica, in support of the meteorite field program. CRREL Spec. Rep., **80**(23), 9 p.

NAGATA, T. (1978): A possible mechanism of concentration of meteorites within the Meteorites Ice Field in Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **8**, 70–92.

NARUSE, R. (1978): Surface flow and strain of the ice sheet measured by a triangulation chain. Mem. Natl Inst. Polar Res., Spec. Issue, **7**, 198–226.

NISHIO, F. and ANNEXSTAD, J. O. (1979): Glaciological survey in the bare ice area near the Allan Hills in Victoria Land, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **15**, 13–23.

NISHIO, F. and ANNEXSTAD, J. O. (1980): Studies on the ice flow in the bare ice area near the Allan Hills in Victoria Land, Antarctica. Mem. Natl Inst. Polar Res., Spec. Issue, **17**, 1–13.

YANAI, K. (1979): Meteorites search in Victoria Land, Antarctica, during field season 1977–1978 austral summer. Mem. Natl Inst. Polar Res., Spec. Issue, **12**, 1–8.

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