THE METHOD OF DETERMINING INFRARED DIAMETERS

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Over the past decade, largely because of the pioneer work of F. J. Low in Tucson, it has become possible to make accurate and reliable astronomical measurements at infrared wavelengths as long as 20 μm. At such wavelengths we see solar system bodies not by reflected sunlight but by their own thermal emission. The larger asteroids, though subtending small angles, give signals at 10 μm comparable in intensity with those from the brightest stars. It is now possible to determine the absolute flux from such asteroids to an accuracy of about 10 percent. Because an asteroid might reasonably be expected to have no atmosphere and no internal source of heat, the thermal radiation it emits must just balance the solar radiation it absorbs, and the measured flux will depend only upon its size. Infrared measurements therefore provide an opportunity to determine the diameters of the brighter asteroids.

ASSUMPTIONS

Certain assumptions must be made before the infrared flux can be converted into a diameter. The ideal asteroid must not rotate (when viewed from the Sun) and must be a smooth spherical blackbody at the observing wavelength ($\sim$ 10 μm). In addition, the proportion of solar energy scattered by each element of surface must be represented by a single albedo, A (the Bond albedo). Then a measurement of the optical flux from the asteroid gives us the product $d^2A \equiv p$, where d is the diameter. The absorbed solar energy is proportional to $1 - A = 1 - p/d^2$, and the infrared flux is a complex function of d^2 that has previously been derived (Allen, 1970). Each infrared measurement can be converted directly to a diameter. In view of the assumptions made in defining this dimension, it will be called the infrared diameter. The relationship between infrared and true diameter is discussed below.

RESULTS

The infrared facility at the University of Minnesota (Ney and Stein, 1968) has been used to determine the infrared diameters of Ceres and Juno (Murdock, unpublished) and Vesta (Allen, 1970). The results are given in table I. It will be seen that in each case the infrared diameter exceeds Barnard's

TABLE I.–*Infrared Diameters of Three Asteroids*

Asteroid	Number of determinations	Infrared diameter, km	Barnard's diameter, km	Density, g-cm^{-3}	Reference to mass
Ceres	6	1160 ± 80	770	1.6 ± 0.7	Schubart (1970)
Juno	4	290 ± 20	220	–	–
Vesta	11	570 ± 10	380	2.5 ± 0.7	Hertz (1968)

micrometer measures by about 50 percent, but that the corresponding densities seem more reasonable than those obtained by using Barnard's values (5.5 for Ceres and 8.5 for Vesta).

DISCUSSION OF RESULTS

An asteroid will not, in general, be ideal, and the infrared diameter may bear little relationship to the linear dimension. For the larger bodies, at least, the figures will be similar. Table II shows the effect on the infrared diameter caused by a breakdown of the various assumptions.

TABLE II.–*Breakdown of Assumptions*

Assumption	Effect on diameter, percent	Sense[a]
Blackbody	< 5	+
Shape, roughness	15 to 35	–
Rotation:		
Dust	15	+
Rock	50	+
Albedo	8	±
Absolute calibration	5	±

[a]+: linear diameter is greater than infrared diameter; –: linear diameter is less than infrared diameter.

Blackness

Observations at two or three wavelengths in the 8 to 14 μm atmospheric window and around 20 μm have shown that Ceres, Juno, and Vesta are graybodies to within experimental uncertainty. Observations of the Moon and Mercury show these bodies to be close to black. It seems unlikely that asteroids have emissivities below 0.95.

Roughness

The Moon and Mercury at full phase emit 30 percent more flux than would a smooth sphere because mountain slopes predominantly seen near the limb are warmer than level terrain. In the extreme an asteroid might emit as a flat disk; the infrared diameter would then be 35 percent too large.

Rotation

If an asteroid rotates, it emits some of its thermal radiation on the night side and the signal received at Earth is reduced. The exact reduction depends on the period and on the nature of the surface. The table shows the magnitude of the effect for a rotation period equal to that of Vesta and for two types of surface–solid rock and porous dust. We expect the largest asteroids to retain a cover of dust, as does the Moon, but smaller bodies with weaker surface gravities will probably behave as solid rock, and the infrared diameter will be much too low.

Albedo

Even if the reflected sunlight is not well represented by the Bond albedo, the effect on an asteroid's diameter is slight. The figure in the table refers to a factor 2 error in albedo.

Variability

There is no evidence for variation of the infrared flux from the three asteroids discussed above. Matson[1] has, however, found some to vary considerably. In such cases, simultaneous optical and infrared measurements are needed to determine whether the variations are caused by changing albedo or shape or both.

CONCLUSIONS

With current detectors it is possible to measure reliable infrared diameters for several dozen asteroids. Notwithstanding the errors and uncertainties, these may be the most reliable dimensions currently available. When more accurate diameters are measured (Dollfus[2]), the infrared data will give us information on the roughness and thermal properties of the asteroids.

REFERENCES

Allen, D. A. 1970, Infrared Diameter of Vesta. Nature **227,** 158.
Hertz, H. G. 1968, Mass of Vesta. Science **160,** 299.
Ney, E. P., and Stein, W. A. 1968, Observations of the Crab Nebula. Astrophys. J. **152,** L21.
Schubart, J. 1970, The Mass of Ceres, IAU Circ. 2268.

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[1]See p. 45.
[2]See p. 25.

DISCUSSION

ALLEN (in reply to a question by KenKnight): In the rotation calculation, I assumed Earth to be on the asteroid's equator. If we look pole-on, rotation has no effect. The corrections to infrared diameters are reduced if we do not face their equators.

BRECHER: F. C. Gillett of UCSD has communicated to me the results of his independent observations of the three largest asteroids in the infrared, namely that high surface temperatures of 245 to 270 K were obtained. The blackbody temperature in that region of the belt should be ~170 K. What sort of assumptions about albedos, etc., does one have to make to account for such a large discrepancy between expected and observed surface temperature of asteroids?

ALLEN: There are two points . . . first, I do not agree with your calculated temperature and find values around 240 K more appropriate. Secondly, the apparent temperature for a spread of temperatures from subsolar point to limb varies with observing wavelengths, and this effect must be taken into account.

ALLEN (in reply to a question by Bender): I use as the basic temperature the subsolar point temperature equivalent to a flat body facing the Sun; the temperature varies across the disk. If an asteroid rotates, the temperature is reduced.

ANONYMOUS: I am worried by the low densities implied by the diameter for Ceres. To get densities down to 1.6 $g\text{-}cm^{-3}$ or so you must assume a proportion of ice, and this has important consequences for the stability of Ceres or any body of that size.

ALLEN: Do not overinterpret the densities I give; I was a bit hesitant about including them in the slide at all. The figure for Ceres was 1.6, but this varies as the third power of the diameter; when you take into account the uncertainties, it could be anywhere from 0 to 4.

SCHUBART (in reply to a request by Chairman Dubin to comment on this paper): The infrared diameters are very valuable because they indicate the sign of possible errors in the diameters measured earlier.

GEHRELS (editorial comment added after the conference): Barnard's value for Vesta may need some revision: Using the diameters of Dollfus[3] and the masses of Schubart[4] one obtains 5 $g\text{-}cm^{-3}$ for both Ceres and Vesta. Also see the discussion after the diameter paper of Dollfus.[3]

As for the smaller bodies behaving as solid rocks, this may be an incorrect concept. (See the paper by Hapke,[5] the polarization paper of Dollfus,[6] and discussion remarks by Anders.[7]) Of course, one needs a much thicker layer of dust against infrared penetration than for visual light.

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[3]See pp. 25 and 29.
[4]See p. 33.
[5]See p. 67.
[6]See p. 95.
[7]See p. 115.