

the order of  $10^{-3}$  atmosphere, the first major constituents to condense consist of calcium, aluminium, and titanium oxides and silicates, such as corundum, perovskite, and melilite. As the gas continues to cool, metallic iron, alloyed with nickel, will be precipitated, and shortly thereafter magnesium silicates will condense<sup>9</sup>.

I have recently constructed models of the primitive solar nebula, in which the internal temperatures and pressures are related by the adiabat likely to be produced on compression of the gas as it reaches the adiabatic state in the collapse of an interstellar gas cloud<sup>10</sup>. In such models, the temperature increases progressively toward the centre of the primitive solar nebula, and the interstellar grains are completely evaporated only near the central spin axis. I have also concluded that planetary bodies should accumulate very rapidly within such a primitive solar nebula<sup>11</sup>. In this picture it is a natural conclusion that the high mean density of the planet Mercury results from its accumulation from material in the primitive solar nebula in the temperature range in which metallic iron has condensed but the magnesium silicates have not. Lewis has independently reached this same conclusion<sup>12</sup>.

Grossman<sup>9</sup> has pointed out that the calcium and aluminium-rich inclusions in the Allende meteorite can be formed inside the region of iron condensation in the primitive solar nebula, because their compositions are consistent with the very highest temperature condensates. If Anderson is correct in his conclusion that the bulk composition of the Moon resembles that of the Allende inclusions, then the natural place for the formation of the Moon in the solar system is inside the orbit of Mercury, through planetary accumulation from the condensed material to be found there.

This explains the anomalous large eccentricity (0.206) of the orbit of Mercury. The temperature gradient in the primitive solar nebula was probably steep enough for the orbital radii at which the Moon and Mercury were formed to differ by a much smaller relative amount than do the orbits of other neighbouring planets within the solar system. Thus gravitational perturbations of the orbits of the two bodies would probably accumulate until a close approach took place, at which a very large modification in the elements of the Moon's orbit would become possible. If the modified orbit of the Moon were sufficiently great to allow it to approach the Earth, then gravitational capture of the Moon by the Earth would become possible, even if improbable.

The semi-major axis of the orbit of Mercury is 0.387 astronomical units (a.u.). The eccentricity of this orbit is 0.206. Thus the aphelion distance of the orbit is at 0.467 a.u. It is reasonable to suppose that Mercury may have originally been in a circular orbit having a radius of 0.467 a.u.

The total energy, kinetic and potential, of a planet in orbit about the Sun is  $G M m / 2a$ , where  $M$  is the mass of the Sun,  $m$  is the mass of the planet, and  $a$  is the semi-major axis of the orbit. In transforming from a circular orbit with  $a = 0.467$  a.u. to the present orbit, the total energy of the orbit of Mercury would be decreased (algebraically) by  $6.38 \times 10^{38}$  erg. It is interesting to see what consequences would follow if this amount of energy should be transferred to the orbit of the Moon.

If the Moon started in a circular orbit at about 0.33 a.u. from the Sun, and was perturbed into an orbit having this distance as perihelion and an aphelion distance of about 1 a.u., then the semi-major axis of the transformed orbit will be about 0.67 a.u. The change of orbital energy required to produce this orbit is less than the above change in the orbital energy of Mercury. In fact, an initial circular orbit for the Moon could be situated as close to the Sun as 0.28 a.u. and be transformed into an orbit with a perihelion at this distance and an aphelion at the distance of the Earth.

Thus the chemical evidence pointing toward the formation of the Moon inside the orbit of Mercury is compatible with the dynamical requirement that the transformation of an initial circular orbit of Mercury into the present orbit of

relatively large eccentricity should provide enough energy to transform the orbit of the Moon in such a way that the Moon crosses the orbit of the Earth.

The precise figures used in this analysis should be regarded as only illustrative. If the orbital perturbations occurred before the primitive solar nebula had been dissipated, the additional mass would modify the gravitational potential so that it was not quite inversely proportional to the distance from the central spin axis, and these figures would require modification. Also, even after dissipation of the primitive solar nebula, the Sun was probably much more massive than at present, because the T Tauri phase of mass loss would only be beginning. This would modify the numbers but not their relative orders of magnitude.

The above considerations pose a reasonably well defined problem for workers on the dynamical problem of capture of the Moon by the Earth, but they do not give its solution. The suggested orbit of the Moon, as perturbed by Mercury, is likely to be transformed further through perturbations by Venus and the Earth, but even so the approaches to the Earth will occur at a significant hyperbolic velocity. The most recent calculations on the dynamical capture process<sup>2</sup> have not yet determined the range of hyperbolic velocities which can be tolerated in this process.

The Earth probably acquired much of its present content of the more volatile elements by sweeping up smaller bodies in the vicinity of its orbit after the dissipation of the primitive solar nebula. Because the abundances of these elements in the Moon are so low, the capture of the Moon by the Earth probably did not occur until after this sweeping action of the Earth was almost complete.

As the lunar exploration programme has progressed, there has been an increasing tendency to regard the Moon as a planetary body in its own right. The conclusions above seem to justify this judgment.

This research has been supported by grants from the National Science Foundation and the National Aeronautics and Space Administration.

A. G. W. CAMERON

*Belfer Graduate School of Science, Yeshiva University,  
New York, New York, and  
NASA Goddard Institute for Space Studies,  
New York, New York*

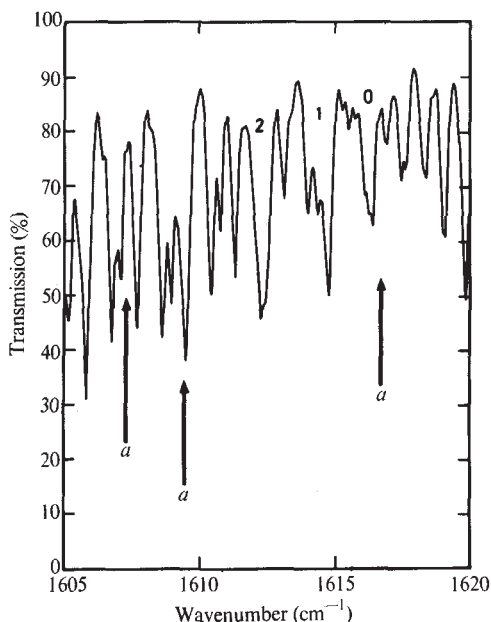
Received September 1, 1972.

- <sup>1</sup> Kaula, W. M., *Revs. Geophys. Space Phys.*, **9**, 217 (1971).
- <sup>2</sup> Singer, S. F., *EOS. Trans. Am. Geophys. Union*, **51**, 637 (1970).
- <sup>3</sup> Cameron, A. G. W., in *The Earth-Moon System* (Marsden, B. G., and Cameron, A. G. W., eds.) (Plenum Press, New York, 1966).
- <sup>4</sup> Cameron, A. G. W., *EOS. Trans. Am. Geophys. Union*, **51**, 628 (1970).
- <sup>5</sup> Hanks, T. C., and Anderson, D. L., *Phys. Earth Planet Int.* (in the press).
- <sup>6</sup> Anderson, D. L., preprint, *IAGC Symp. Cosmochem.* (Cambridge, Mass., August 1972).
- <sup>7</sup> Sonett, C. P., Schubert, G., Smith, B. F., Schwartz, K., and Colburn, D. S., *Geochim. Cosmochim. Acta Suppl.*, **2**, 2415 (1971).
- <sup>8</sup> Marvin, U. B., Wood, J. A., and Dickey, jun., J. S., *Earth Plan. Sci. Lett.*, **7**, 346 (1970).
- <sup>9</sup> Grossman, L., *Geochim. Cosmochim. Acta*, **36**, 597 (1972).
- <sup>10</sup> Cameron, A. G. W., and Pine, M. R., *Numerical Models of the Primitive Solar Nebula, Icarus* (in the press).
- <sup>11</sup> Cameron, A. G. W., *Accumulation Processes in the Primitive Solar Nebula, Icarus* (in the press).
- <sup>12</sup> Lewis, J. S., *Earth Plan. Sci. Lett.*, **15**, 286 (1972).

## Stratospheric Nitrogen Dioxide from Infrared Absorption Spectra

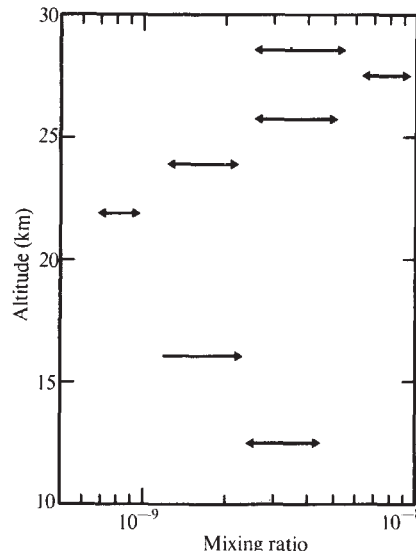
STRATOSPHERIC absorption due to  $\text{NO}_2$  has been identified<sup>1-3</sup> in infrared spectra of the solar radiation recorded from balloon borne gondolas floating at mid-latitudes in the altitude range

of 30 km when the solar zenith angle is larger than 91°. In this particular geometric situation most of the absorption by the atmosphere takes place at altitudes smaller than float altitude over very long optical paths. This offers two great advantages: the sensitivity of the absorption method is maximum and the quantitative interpretation is easier because absorption takes place mostly at constant total pressure, constituent concentration and temperature where the solar radiation passes closest to the Earth's surface.



**Fig. 1** Synthetic absorption spectrum of a portion of the  $\nu_3$  band of  $\text{NO}_2$  computed on the basis of the available spectroscopic data<sup>4</sup> and calibrated in absolute value by means of the laboratory measurements of Guttman<sup>6</sup>; optical thickness: 0.014 atm cm; total pressure: 1.18 atm; temperature: 298 K. The position of water vapour lines is indicated (a), one of them overlapping the  $\text{NO}_2$  absorption marked 0. Absorptions 1 and 2 are unaffected by water vapour and appear clearly in the atmospheric spectra.

A quantitative interpretation of the available data leading to stratospheric mixing ratios of  $\text{NO}_2$  from the edge of the tropopause at 12 km up to 28 km is reported here. Synthetic spectra have been computed on the basis of the spectroscopic constants given for  $\text{NO}_2$  by Olman and Hause<sup>4</sup> using a Lorentz line full half width of  $0.16 \text{ cm}^{-1}$  in STP conditions. The choice of this value is based on the work of Yamamoto and Aoki<sup>5</sup>. The line intensity was determined by comparing the integrated synthetic spectra with the integrated absorption measured in the laboratory by Guttman<sup>6</sup>. Fig. 1 shows the transmission versus wavenumber of a portion of the  $\nu_3$  band computed for the laboratory conditions used by Guttman<sup>6</sup>. The positions of water vapour lines are shown at the wave numbers given by Benedict and Calfee<sup>7</sup>. One of these overlaps the  $\text{NO}_2$  absorption feature numbered 0 on the figure. Absorptions numbered 1 and 2 are very well isolated; we have used chiefly this part of the spectrum, particularly well marked in the atmospheric recordings<sup>3</sup>, chiefly for the quantitative interpretation. The  $\nu_1 + \nu_3$  band<sup>1,2</sup> underlies very clearly the P branch of the  $\nu_3$   $\text{CH}_4$  band. The mixing ratios by volume shown in Table 1 and Fig. 2 refer to the altitudes of the solar grazing rays and have been deduced from the  $\text{NO}_2$  concentrations determined from the spectra and the total concentration given in the Mid-Latitude, Spring-Fall model of US Standard Atmosphere Supplements, 1966. The quoted errors correspond to lower and upper values of the amount of absorber in the optical path leading to computer generated spectra that could be distinguished from the observed atmospheric spectra.



**Fig. 2** Stratospheric  $\text{NO}_2$  mixing ratio by volume.

We believe that the relatively high value observed at the lowest altitude is due to a tropospheric influence. The mixing ratio seems to increase from 20 to 28 km showing the presence of a stratospheric layer of  $\text{NO}_2$ . This might be why no evidence for  $\text{NO}_2$  has been found up to now in submillimetre stratospheric emission spectra<sup>8</sup> taken from an altitude of 12 km at a zenith angle of 75°.

**Table 1** Mixing Ratios relative to Zenith Angle

Balloon altitude (km)	Solar zenith angle	Grazing solar rays altitude (km)	$\text{NO}_2$ mixing ratio by volume	Observed band	Reference to spectra
29	94.1	12.5	$(3.4 \pm 1) \times 10^{-9}$	$\nu_1 + \nu_3$	(1, 2)
34	94.3	16.1	$< 2.3 \times 10^{-9}$	$\nu_1 + \nu_3$	(1, 2)
29.7	92.8	21.9	$(8.3 \pm 1.5) \times 10^{-10}$	$\nu_3$	(3)
29.7	92.4	23.9	$(1.7 \pm 0.5) \times 10^{-9}$	$\nu_3$	(3)
29.7	92.0	25.7	$(3.8 \pm 1.3) \times 10^{-9}$	$\nu_3$	(3)
29.7	91.5	27.5	$(7.8 \pm 1.5) \times 10^{-9}$	$\nu_3$	(3)
29.7	91.2	28.3	$(4.0 \pm 1.5) \times 10^{-9}$	$\nu_3$	(3)

Following the theoretical investigation made by Nicolet<sup>9</sup> on the role of  $\text{NO}_2$  on the stratospheric ozone, the values listed in Table 1 indicate an influence of natural nitrogen dioxide on  $\text{O}_3$ . In sunset conditions as is the case for these determinations,  $\text{NO}_2$  mixing ratios can be taken, within experimental errors, equal to  $\text{NO}_x$ .

M. ACKERMAN  
C. MULLER

*Institut d'Aéronomie Spatiale de Belgique,  
3 Avenue Circulaire,  
Brussels, Belgium*

Received July 31, 1972.

- Ackerman, M., and Frimout, D., *Bul. Acad. Roy. Belgique*, **55**, 948 (1969).
- Ackerman, M., *Space Sci. Rev.* (in the press).
- Goldman, A., Murcray, D. G., Murcray, F. H., Williams, W., and Bonomo, F. S., *Nature*, **225**, 443 (1970).
- Olman, M. D., and Hause, C. D., *J. Mol. Spectr.*, **26**, 241 (1968).
- Yamamoto, G., and Aoki, T., *J. Quant. Spectr. Radiat. Transfer.*, **12**, 227 (1972).
- Guttman, A., *J. Quant. Spectr. Radiat. Transfer.*, **12**, 1 (1962).
- Benedict, W. S., and Calfee, R. F., ESSA professional paper 2 (US Department of Commerce, Washington, 1967).
- Harries, J. E., Swann, N. R., Beckman, J. E., and Ade, P. A. R., *Nature*, **236**, 159 (1972).
- Nicolet, M., in *Mesospheric Models and Related Experiments* (Reidel, Dordrecht, 1971).