THE ASTROPHYSICAL JOURNAL, 234:L155–L158, 1979 December 1

TEMPORAL CHARACTERISTICS OF THE JOVIAN ATMOSPHERE

JOHN CALDWELL,[1] ROBERT D. CESS, AND BARBARA E. CARLSON
Laboratory for Planetary Atmospheres Research
State University of New York, Stony Brook

ALAN T. TOKUNAGA[1]
Steward Observatory
University of Arizona

F. C. GILLETT
Kitt Peak National Observatory[2]

AND

I. G. NOLT[1]
Atmospheric Physics and Chemistry Laboratory
NOAA, Boulder, Colorado
Received 1979 July 9; accepted 1979 August 9

ABSTRACT

Drift scans along the central meridian of Jupiter have been obtained at wavelengths of 7.9, 17.8, and 19.7 μm. These observations indicate a significant north-south temperature asymmetry within the Jovian stratosphere but not within its troposphere, results which agree with the recent *Voyager 1* observations. Employing a time-dependent stratospheric model, we find that the observed north-south asymmetry is consistent with seasonal stratospheric variability. In the model, the primary cause for this variability is the time-dependent absorption of sunlight by aerosols.

Subject headings: planets: atmospheres — planets: Jupiter

I. INTRODUCTION

The possibility of significant seasonal variability within the atmosphere of Jupiter has generally been disregarded, since this planet has an obliquity of only 3°.1. But in the following section we present ground-based observations which demonstrate that at high latitudes the Jovian stratosphere is warmer in the northern hemisphere than in the southern hemisphere, a finding consistent with recent *Voyager 1* observations. This hemispheric asymmetry in stratospheric temperature is suggestive of seasonal effects, since this temperature is strongly dependent upon solar absorption by atmospheric constituents. Despite the small obliquity, such solar absorption will undergo seasonal variability. At deeper levels within the atmosphere (troposphere), where direct solar absorption by atmospheric constituents does not strongly influence tropospheric temperature, the observations do not indicate significant hemispheric temperature asymmetry.

To test the hypothesis that Jupiter's stratosphere does undergo seasonal variability, we present in § III results for a time-dependent stratospheric seasonal model, comparing northern versus southern hemisphere poles. The model is compatible with the existing observations, and shows that there is a phase lag in the Jovian seasons amounting to as much as one quarter of the Jovian year. This means that the north pole is now experiencing maximum stratospheric temperatures, since the northern hemisphere is currently near its autumnal equinox. At the same time, stratospheric temperatures are minimum at the south pole, since this is the termination of the south polar night. Thus, according to the model, the current Jovian equinox denotes a time at which there should be maximum hemispheric asymmetry in stratospheric temperature.

[1] Visiting Astronomer, Kitt Peak National Observatory.

[2] Operated by the Association of Universities in Astronomy, Inc., under contract with the National Science Foundation.

II. THE OBSERVATIONS

As part of a continuing program to monitor infrared emission from the giant planets, and thereby to study their seasonal characteristics (Tokunaga *et al.* 1979), spatially resolved drift scans were made along the central meridian of Jupiter on 1978 January 26 and 1979 March 8 using the 4 m telescope of the Kitt Peak National Observatory. Scans at 7.9, 17.8, and 19.7 μm are shown in Figures 1 and 2 (Plate L24). Details of the observations are summarized in Table 1.

The data at 7.9 μm occur in the wing of the strong ν_4 fundamental of CH_4. Radiation at this wavelength comes primarily from the vicinity of the 10 mbar pressure level (Orton 1977, Fig. 3), which is within the Jovian stratosphere. The dominant feature of this scan is the strong north-south asymmetry, amounting to 70% in brightness for regions where |latitude| > 60°. Departures from monotonicity between these extremes will be discussed shortly. The general nature of this scan is confirmed by several scans taken on a previous night, which were made with a smaller telescope

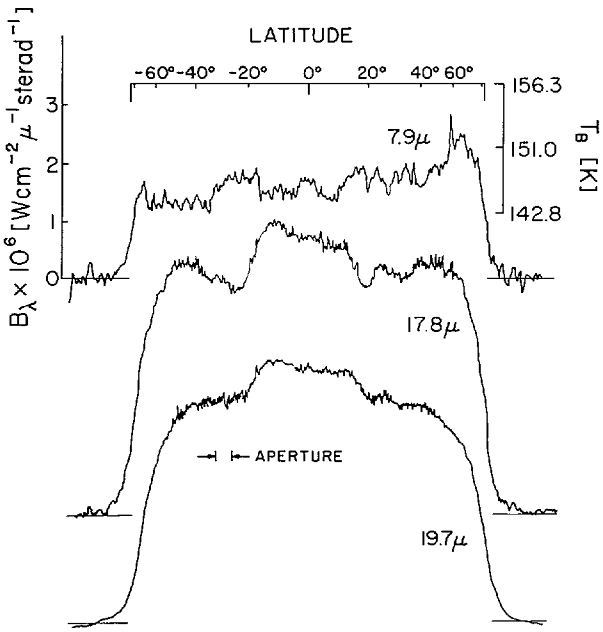

FIG. 1.—North-south scans along the central meridian of Jupiter on 1979 March 8. Brightness and brightness temperatures are shown for the 7.9 μm scan.

TABLE 1

SUMMARY OF OBSERVATIONS MADE USING THE 4 METER TELESCOPE AT KPNO

λ(μm)	Start Time (UT)	Date	Scan Rate (arcsec s^{-1})	LCM1	LCM2
17.8....	6:15	1978 Jan 26	0.2	187	82
17.8....	7:35	1979 Mar 8	0.5	230	266
19.7....	7:41	1979 Mar 8	0.5	233	270
7.9....	7:56	1979 Mar 8	0.125	242	279

NOTE.—Photometry aperture size: 1 mm = 1″75.

under greatly inferior seeing conditions. The data are also in excellent qualitative agreement with the recent *Voyager 1* observations corresponding to the 10 mbar level (Hanel *et al.* 1979, Fig. 4).

The other two scans in Figure 1 correspond to altitudes below 100 mbar (Orton 1977) in the Jovian troposphere. Here there is no comparable north-south asymmetry, which is also consistent with the *Voyager 1* data. Instead, the thermal emission exhibits non-monotonic latitudinal variations. Note the anticorrelation between the detailed structure of the 17.8 μm scan in Figure 1 and the corresponding 7.9 μm scan. This suggests that the mechanisms which cause tropospheric features also influence the stratosphere.

The details of the thermal emission at 17.8 μm are stable in time, and they correlate well with the classical visual belt and zone structure of the planet. This is demonstrated in Figure 2, where north-south scans made 13.5 months earlier than those in Figure 1 are compared with contemporary green and ultraviolet images. Note that the latitudinal variation at 17.8 μm has changed only slightly over this time baseline. There is a slight depression at latitude 35° in 1979 that is not evident in 1978. Also note the strong correlation with visual features in the sense that darker regions correspond to greater thermal emission at 17.8 μm.

In summary, these observations indicate that Jupiter has a stratospheric north-south temperature asymmetry and a more complex tropospheric temperature structure, and that the latter persists at least over time scales comparable to a terrestrial year. In the following section, we present a model that is consistent with the stratospheric characteristic, as well as the temporal stability of the troposphere. We do not address the complexity of the troposphere.

III. THE MODEL

The observations discussed above were made just before autumnal equinox in the northern hemisphere of Jupiter. A previous study of Saturn (Cess and Caldwell 1979) indicates that maximum north polar and minimum south polar stratospheric temperatures would coincide with the northern hemisphere autumnal equinox, the former being due to a 90° phase lag with the insolation cycle, and the latter corresponding to the termination of the south polar night. Since the Jovian stratospheric observations are qualitatively consistent with the Saturn model, it was decided to investigate the model's applicability to Jupiter.

The obliquity of Jupiter is only 3°.1, compared with Saturn's 26°.7. However, this value of the Jovian obliquity is sufficient to give rise to a significant seasonal insolation influence. For example, Cess and Caldwell (1979) show that the ratio of stratospheric polar to equatorial heating due to near-infrared CH_4 absorption is 2.62 $(\tan \delta)^{1/2}$, which follows from their equations (11) and (12), with δ denoting the solar declination angle.[3] This illustrates that at summer solstice, the polar heating due to CH_4 absorption is 61% as great as the equatorial heating. Since the polar heating due to insolation is zero during the polar night, this range in polar heating could conceivably drive a significant seasonal effect.

Moreover, we have calculated the ratio of stratospheric response time to Jovian year. The corresponding ratio for Saturn was designated "β" by Cess and Caldwell (1979). We find that β(Jupiter) is approximately half β(Saturn), because of increased emission from the warmer atmosphere of Jupiter. This suggests that Jupiter's stratosphere is more responsive than Saturn's to seasonal forcing.

With these two indications that seasonal effects could be significant on Jupiter, we made a time-dependent calculation with nonlinear thermal response. Our Jovian seasonal stratospheric climate model is identical to that for Saturn (Cess and Caldwell 1979), but with atmospheric and radiation parameters appropriate to Jupiter taken from Cess and Chen (1975). The only exception is that the polar gravitational

[3] Throughout this paper, this means the angle between the Jovian equatorial plane and the Sun direction.

acceleration is 2845 cm s^{-2}. In the model, it is assumed that there is no seasonal variability within the troposphere, consistent with the present observations. The eccentricity and solar declination angle were obtained from the *American Ephemeris and Nautical Almanac.*

The seasonal variation in polar stratospheric temperature is qualitatively similar to that previously reported for Saturn (Cess and Caldwell 1979). As would be expected, the polar temperature decreases during the polar night, prior to the vernal equinox which marks the beginning of the polar day, at which time a temperature increase commences. The polar-day stratospheric temperature exhibits a 90° phase lag with the insolation cycle, the maximum insolation occurring at summer solstice and the maximum temperature occurring at the autumnal equinox, or polar-day sunset.

In Figure 3 we illustrate, for a pressure level of 10 mbars, the seasonal asymmetry between the north and south polar temperatures as predicted by the model. In accordance with the above discussion, the maximum amplitude occurs at equinox. Two cases are illustrated in Figure 3, one which incorporates solar absorption by some unknown absorber, commonly referred to as an "aerosol" or "Axel dust," and the second without this source of solar absorption. The aerosol heating model which we have adopted is the same as that employed in the Saturnian seasonal model, but with aerosol parameters taken from Cess and Chen (1975).

There are two significant features concerning the results shown in Figure 3. The first is that the model with aerosol heating included shows significant north-south polar asymmetry in stratospheric temperature. The second feature is that, by comparison to the curve for no aerosol heating, it is evident that aerosol heating constitutes a significant source of seasonal forcing.

This importance of aerosol heating, within the context of the seasonal model, is easily understood. Since the aerosol is assumed to be optically thin, the zenith-angle dependence of insolation is compensated by the corresponding change in slant path through the aerosol layer (Cess and Caldwell 1979). Thus, for sunlit portions of the planet, the aerosol solar absorption is independent of both latitude and time. Since the fractional length of daytime is always 0.5 at the equator, then, excluding eccentricity effects, there is no seasonal variation in equatorial diurnally averaged aerosol absorption. At the poles, on the other hand, aerosol solar absorption is twice the equatorial value during the polar day, while it is zero throughout the polar night. Thus the aerosol heating produces strong seasonal forcing within the polar stratosphere.

IV. CONCLUDING REMARKS

Unfortunately, the radiation properties of the unknown aerosol constitute the weakest link in our ability to model the thermal structure of the Jovian stratosphere. Furthermore, our model refers only to the poles and to the equator, whereas the finite spatial resolution of our instrument and our viewing direction combine to limit our observations effectively to an average over 20 degrees of latitude near the pole. For these reasons, we attempt no quantitative comparison between model and observations. What we can conclude is that (i) the model suggests that significant high-latitude seasonal variability can exist within Jupiter's stratosphere, despite the small obliquity; (ii) the primary cause for the model-produced seasonal variation is time-dependent aerosol absorption; (iii) the model is qualitatively consistent with the present ground-based and *Voyager 1* observations, in that both the observations and the model indicate that the north-polar stratosphere is currently warmer than that of the south pole; and (iv) for plausible atmospheric parame-

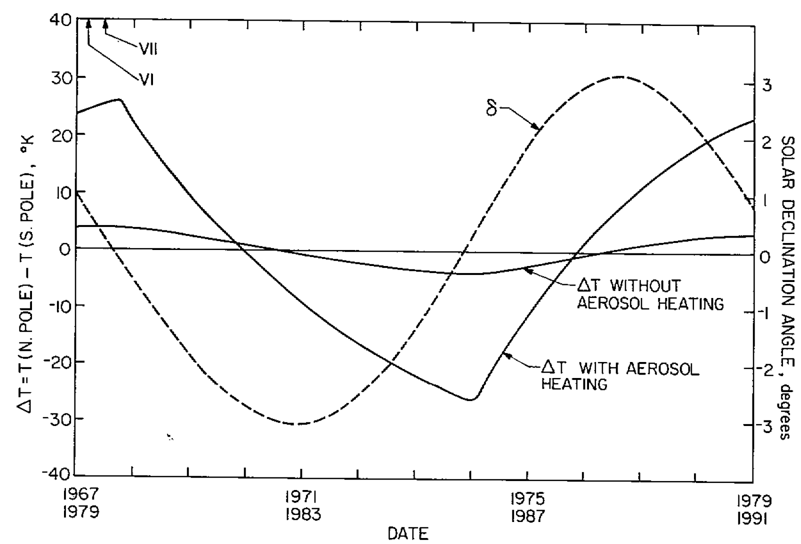

FIG. 3.—Seasonal variation of the difference between north polar and south polar stratospheric temperatures at the 10 mbar level. Also shown is the solar declination angle (*broken line*), and the dates of *Voyager 1* (VI) and *Voyager 2* (VII) encounters. The observations discussed in § II were made just after the VI encounter.

ters, the geometrically precise model shows larger seasonal variations at the poles (Fig. 3) than the spatially degraded observations do for intermediate latitudes (Fig. 1), as it must to be realistic.

Coincidentally, the present ground-based observations, as well as the *Voyager 1* and *2* encounters (see Fig. 3), coincide with a time at which the model predicts maximum stratospheric asymmetry between north and south poles. But the model also predicts that this asymmetry should vanish by about late 1981. In this regard, we look forward to the future availability of ground-based observations of Jupiter.

This work was supported in part by the following grants to SUNY Stony Brook: NSF grant ENG 77-09124 and NASA grant NSG 7320.

REFERENCES

Cess, R. D., and Caldwell, J. 1979, *Icarus*, **38**, 349.
Cess, R. D., and Chen, S. C. 1975, *Icarus*, **26**, 444.
Hanel, R., *et al.* 1979, *Science*, **204**, 972.
Orton, G. S. 1977, *Icarus*, **32**, 41.
Tokunaga, A. T., Caldwell, J., Gillett, F. C., and Nolt, I. G. 1979, *Icarus*, **39**, 46.

John Caldwell, Barbara E. Carlson, and Robert D. Cess: Laboratory for Planetary Atmospheres Research, State University of New York, Stony Brook, NY 11794

F. C. Gillett: Kitt Peak National Observatory, Tucson, AZ 85721

I. G. Nolt: Atmospheric Physics and Chemistry Laboratory, NOAA, Boulder, CO 80309

Alan T. Tokunaga: Steward Observatory, University of Arizona, Tucson, AZ 85721

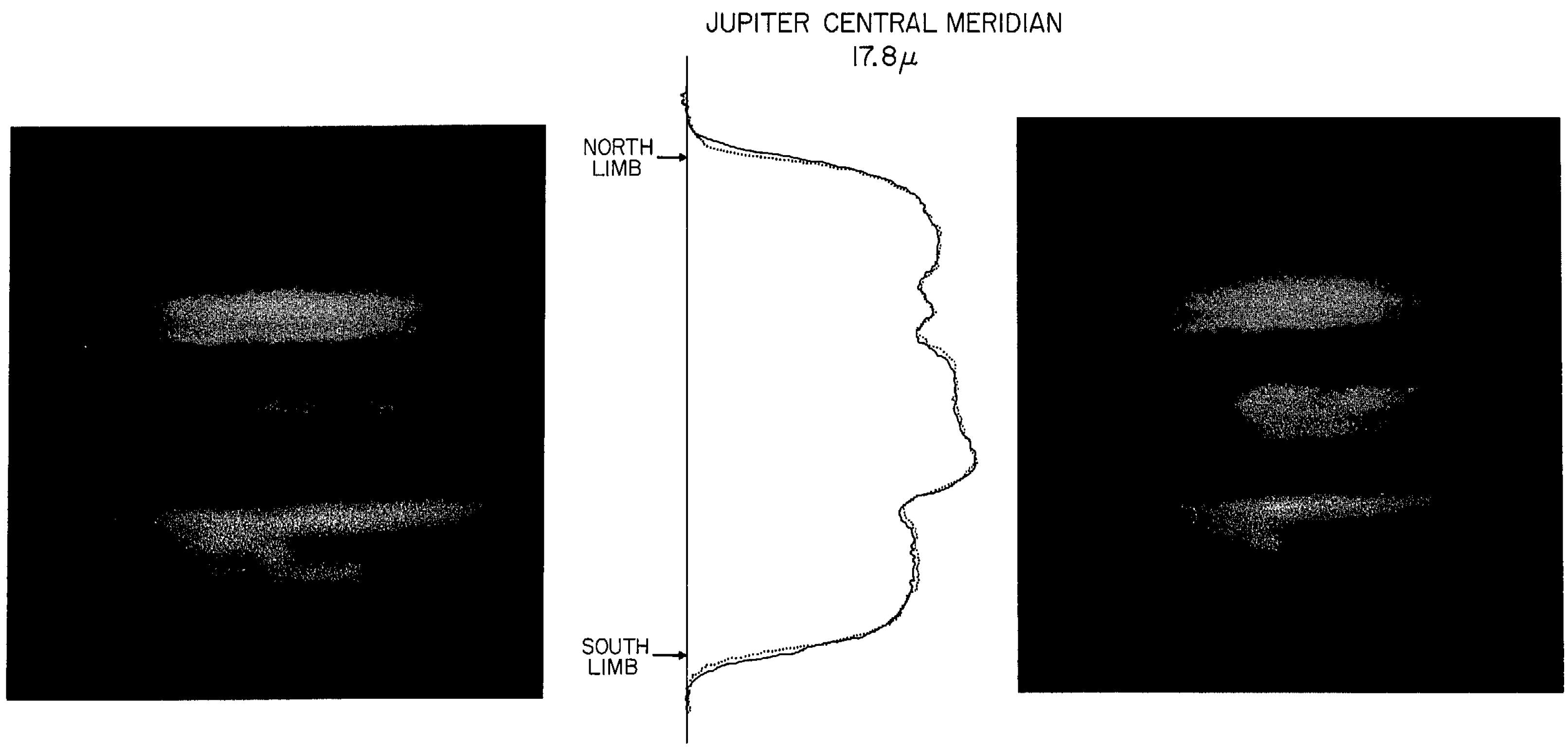

FIG. 2.—A north-south and a superposed south-north scan of Jupiter's central meridian on 1978 January 26 compared with Planetary Patrol composite images obtained 23 days earlier. The images correspond to ultraviolet (*left*) and green (*right*). They were chosen to exclude the Great Red Spot, since it was not earthward during the infrared scans. Lowell Observatory Photograph.

CALDWELL *et al.* (*see* page L155)