Thermal Infrared Emission of the Jovian Disk[1]

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Abstract. The 8–14 micron infrared emission of Jupiter has been observed on six nights in December 1963 using the 200-inch Hale telescope. The new observations possess twice the resolution of those obtained in 1962. The brightness temperature at the center of the disk appears to be nearly constant at 129°K. With some slight ambiguity, the light bands are about 0.5° cooler in appearance than the dark bands. There is some suggestion of morning-evening asymmetry in one of the bands. The Great Red Spot is found to be from 1.5° to 2.0° cooler than the surrounding disk at the newer resolution.

Introduction. We previously reported the first detailed photometry of the thermal radiation emitted by Jupiter in the 8–14 μ wavelength region [*Murray et al.*, 1964; hereinafter referred to as paper 1]. Because of the presence of low-frequency drift in the noise of the Jovian scans of paper 1, as well as difficulties in the Jovographic positioning of signal scans, it was not possible to obtain a map of the distribution of brightness temperature over the disk of Jupiter. Instead, the average limb-darkening curves, both polar and equatorial, were extracted together with an upper bound of 0.5°K contrast between light and dark bands and of the Great Red Spot. In the present study, although the drift has not been altogether eliminated, it has been reduced to the point where brightness temperature maps of significance for Jupiter's gross band structure can be obtained by the superposition and averaging of maps obtained on individual nights.

A low-resolution brightness temperature (averaged over about the inner one-half of the area of Jupiter's disk) of 128°K was measured with a 20-inch telescope on White Mountain in 1962 [*Murray and Wildey*, 1963]. Measurements made about two months later through the 200-inch telescope with a resolution approximately one-seventh of the Jovian disk yielded a brightness temperature at the center of the disk of 128.5°K. The average center-of-the-disk temperature for the present observations is 129°K in which the resolution is approximately one-seventeenth the equatorial diameter. The range of disagreement between these temperatures represents only 11% in specific intensity and is especially favorable when we consider that: (1) The absolute calibration is not based on an extraterrestrial standard but on the use of liquid nitrogen and water-ice cooled blackbodies viewed directly by the photometer. (2) The design of such blackbodies was altered between sets of observations. (Independent laboratory studies showed, however, that their emissivities were all within 1% of unity.) (3) Nominal telescope transmission losses are assumed. (4) A standard atmospheric extinction coefficient and Lambert's law of radiative extinction for correction to outside the earth's atmosphere is assumed. (5) Most or all of the discrepancy can be explained by the differences in spatial resolution. (6) There is no a priori evidence against intrinsic small-scale Jovian variability.

In paper 1 an attempt was originally made to recover position on Jupiter by accurately recording the right ascension and declination read-

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ings at beginnings and endings of right ascension scans across the Jovian disk. However, this procedure was later revealed to be too inaccurate for the purpose, owing, evidently, to the combination of backlash in the telescope drive and especially friction in the telescope's remote read-out. The method finally adopted was to center each scan on that Jovian diameter which was parallel to the local declination circle so that the scan's zero line (sky versus sky signal) was parallel to right ascension. The scan was then moved parallel to itself until the separation between photometer ingress and egress on the Jovian disk, making allowance for the nonzero width of the photometer aperture, coincided with a chord on the Jovian disk. While this method works fairly well for a planet like Venus, where the signal to noise ratio is very high, it is not very satisfactory for Jupiter, because photometer ingress and egress are not well enough defined at the lower signal-to-noise ratio. The problem is, in any case, especially bothersome for almost diametric scans. This problem has been alleviated, for the most part, in the present observations, by photographic monitoring of the visible image.

The observations. The present observations were collected at the east-arm Cassegrain focus of the 200-inch Hale telescope on the nights of December 12, 1963, through December 17, 1963, between approximately 0h 40m and 2h 10m UT. The photometer employed is a modification of the one used in paper 1 [*Westphal et al.*, 1963] so as to allow a variability in the selection of focal plane apertures, a more satisfactory guiding and position-monitoring periscope, a more finely adjustable optical path for calibration, and a reduction of microphonics from the image chopping motor. A newer mercury-doped germanium photoconductor of somewhat higher

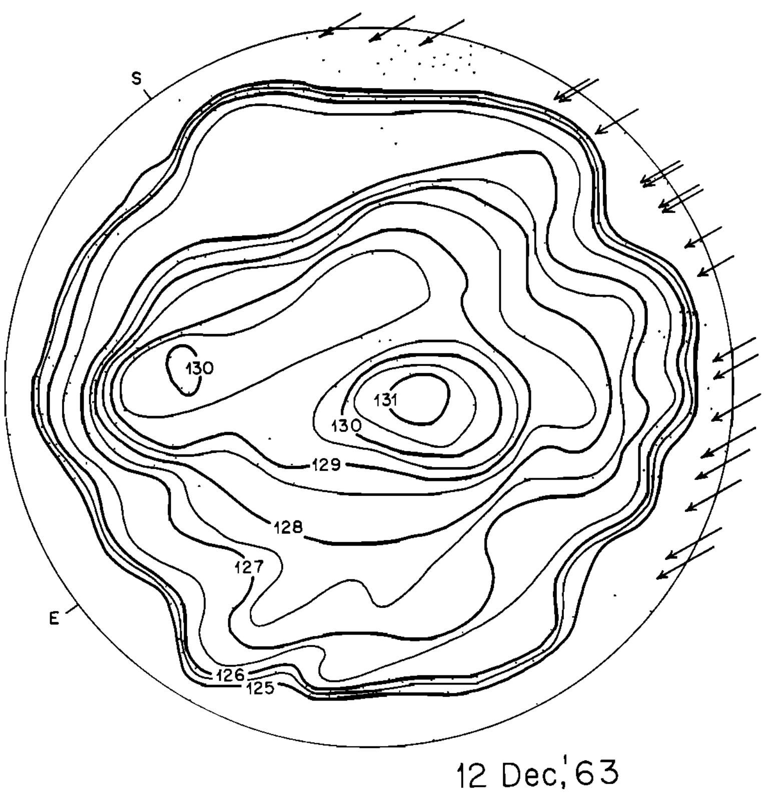

Fig. 1. Brightness temperature map of an individual night. Celestial south and east are indicated at the edge of the disk. The locations of scan tracks are shown by arrows. The orientation of Jupiter's polar axis is shown by the dotted gross visible band structure. Night-to-night variations in maximum brightness temperature may be explainable in terms of extinction fluctuations in the earth's atmosphere.

responsivity at liquid hydrogen temperatures was used. The detecting cell was mounted in the same dewar, but with a longer snout (5 inches), as used in paper 1, and no coolant was used in the outer jacket, where formerly liquid nitrogen had been used. The inner jacket, which directly cools the Hg:Ge cell, was filled with liquid hydrogen.

As before, it was possible to view the region of Jupiter being measured by examining the reflection from the aluminized focal plane diaphragm, the normal to whose plane was angled 45° with respect to the telescope's optical axis. The visible image of Jupiter viewed in this manner has a dark spot corresponding to the 2.5-sec-of-arc entrance aperture to the detector. In place of an eyepiece, a 35-mm single-lens reflex camera, rigidly attached to the photometer, was used to obtain both an eye-view and a photographic record whenever desired of the above Jovian image. The general data reduction technique has already been briefly described [*Westphal et al.*, 1965].

The telescope was set to track in hour angle at a rate which was 2500 sec of arc/hour less than sidereal drive. The maximum period required to scan the image was thus about one minute. Between scans the telescope was readvanced in hour angle by differentially coupling in the fast slow-motion motor without altering the telescope's tracking drive rate. The declination was then changed slightly and another right-ascension scan in the observational sequence was performed. During the course of each scan the camera shutter was tripped while simultaneously triggering an edge marker on the infrared signal trace. On each of one or two scans which passed near the center of the disk, two such tagged photographs were obtained. Thus, the direction of right-ascension with respect to Jupiter's rotational axis was obtained along with a positional reference point and a scale factor relating Jupiter's image to the time axis of the infrared signal.

The brightness temperature maps resulting from the above procedure are shown in Figures

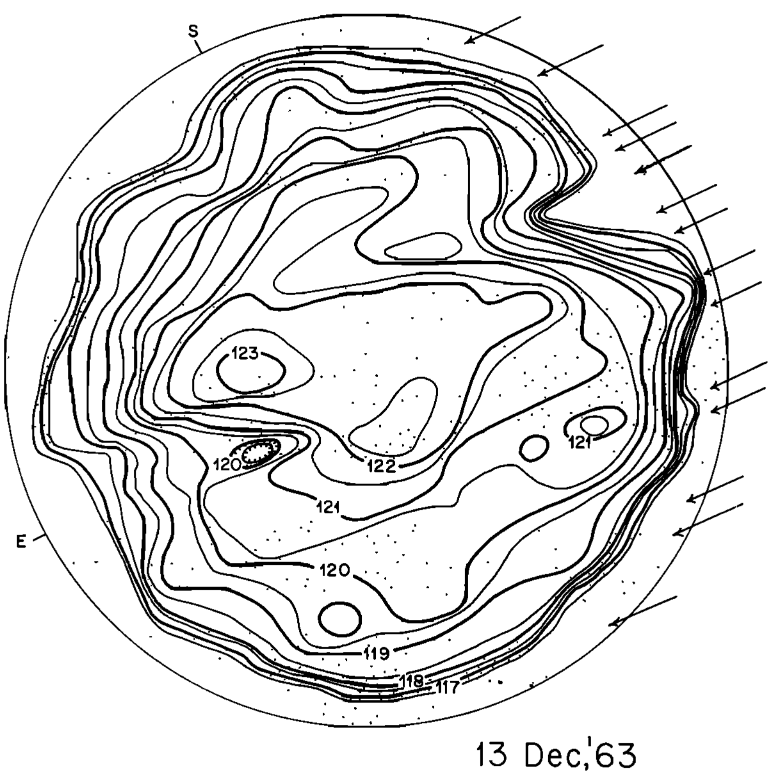

Fig. 2. Same as Figure 1.

1 through 5. The representation of oblateness has been neglected because of relatively low infrared pictorial resolution. The visible band structure (and therefore the orientation of Jupiter's rotational axis as well), which was discernable on the monitor photographs, has been indicated in the figures. The dotted regions represent dark bands. The direction of right ascension and the specific scan tracks from which data were recovered are indicated by arrows. A tendency of isophotic gradients to align themselves parallel to the local declination circle is taken to be an indication primarily of photometric error and secondarily of tracking error, inasmuch as it seems unreasonable to expect the presence of any Jovian anisotropy which especially favors the orientation of the earth's axis.

The seeing and the nonstationary noise were unusually favorable on the night of December 17. The Great Red Spot (GRS) was on the disk that night. There was insufficient time to permit the mapping of the entire disk. The GRS was first measured relative to the adjacent regions of Jupiter by on-off alternation of this image region on the focal plane aperture. It was thus verified that the GRS specific intensity was considerably fainter than the surrounding disk. Following this, four scans, including one in declination, were made across the disk and were determined to pass through the GRS. The scan in declination was made at the fastest permissible rate of 900 sec of arc/hour. Jupiter's image was traced by hand, as far as resolvable, from one of the monitor photographs, and is shown in Figure 6. The individual scan tracks are shown in the figure. The signal traces, also reproduced in Figure 6, have been scaled and positioned so that perpendicular projections onto the corresponding scan tracks reveal the Jovographic source of a given signal. Scan 1 and scan 4, mutually perpendicular, show a closure of the GRS as a cold region of the infrared Jovian disk. Scans 2 and 3 are, respectively, de-emphasized and over-emphasized reproductions of the effect demonstrated on scan

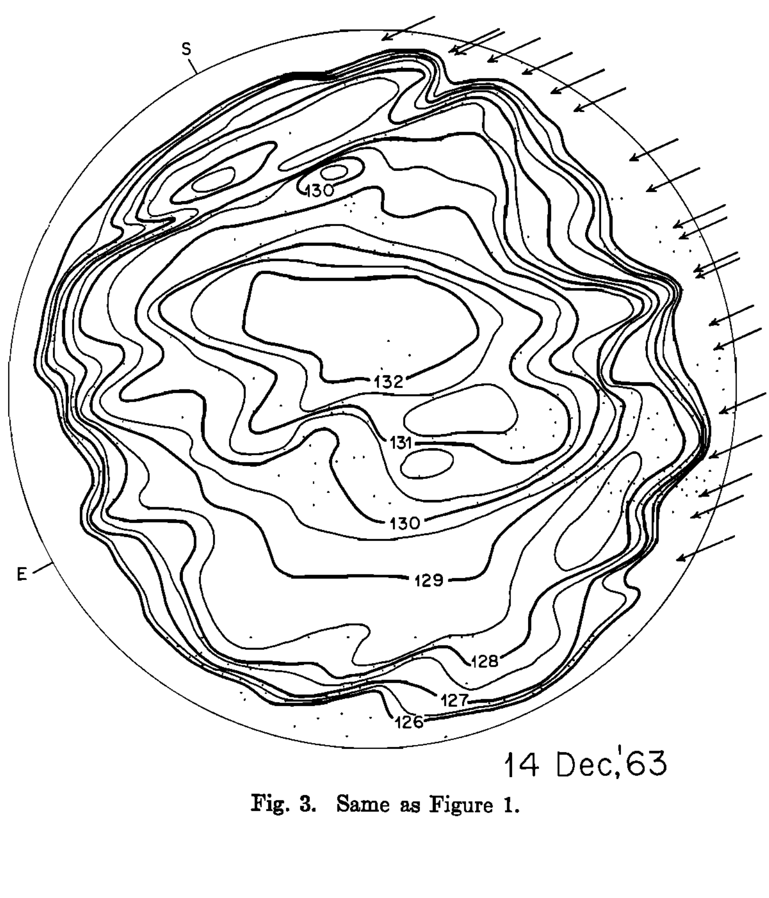

Fig. 3. Same as Figure 1.

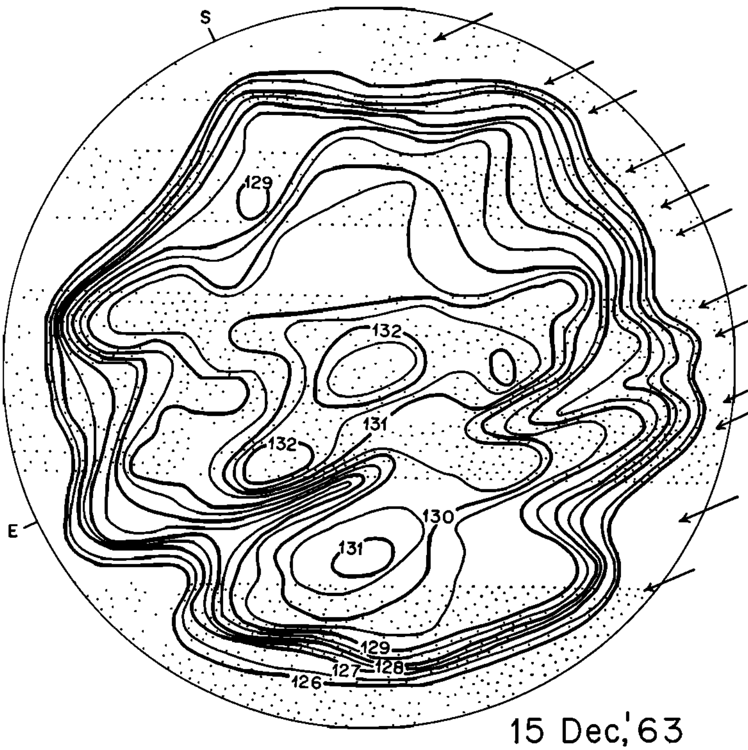

Fig. 4. Same as Figure 1.

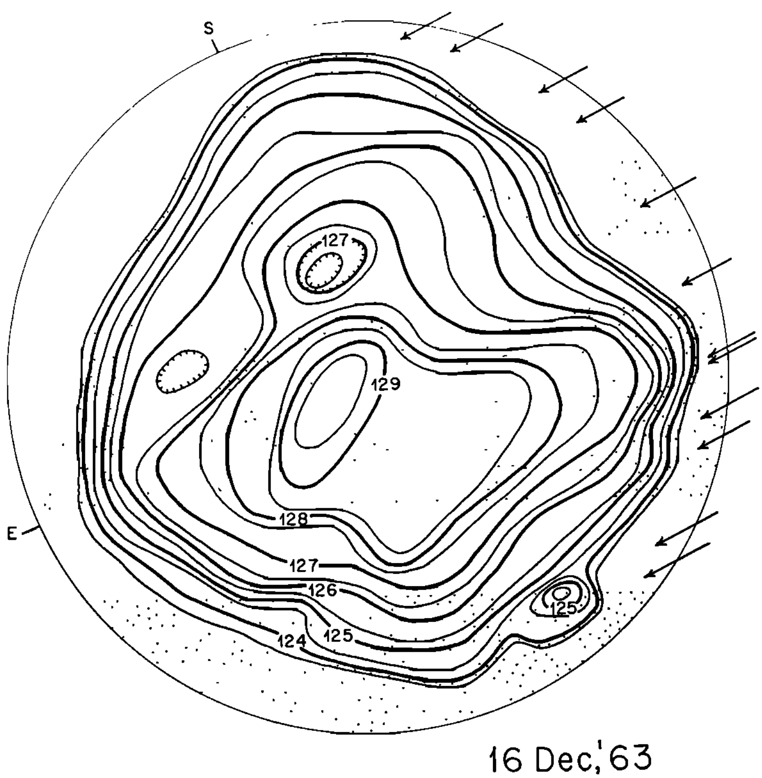

Fig. 5. Same as Figure 1.

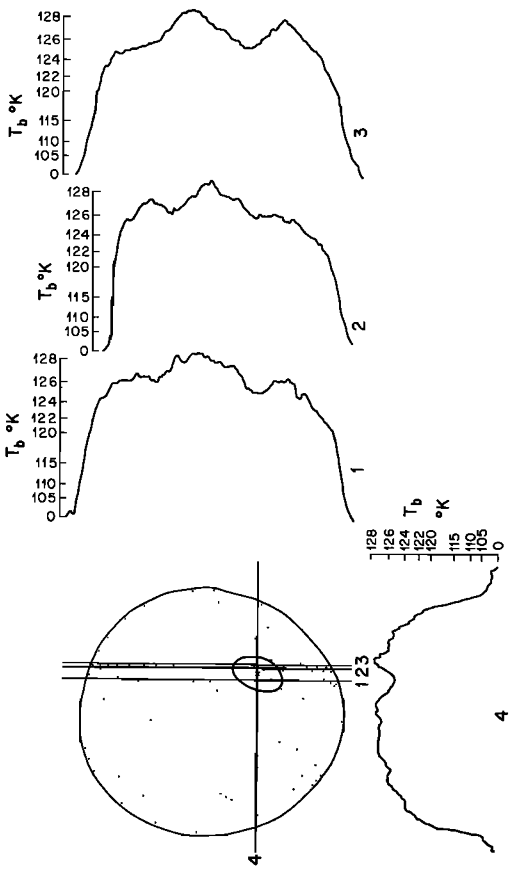

Fig. 6. Diagram of strength and location of Jovian infrared signal recorded on December 17, 1963, at approximately 2 UT. Signals are traced directly from data without noise smoothing and are scaled to the drawing of Jupiter. Closure of the Great Red Spot as a cold region is exhibited.

1 in the vicinity of the GRS. They do nevertheless possess, in this region of the traces, marginal reproduction of scan 1 to within noise expectations. It may be re-emphasized here that the relative coldness of the GRS was first verified absolutely by measuring in a nonscanning on-off mode. The general contrast between the GRS and the surrounding disk appears to be between 1.5° and 2.0°K.

Discussion. A number of fairly small cold and hot spots are shown by the data in Figures 1–5. Their reality is open to question because of the sources of uncertainty discussed in the preceding section, and they should not be considered real without additional confirmation. No high resolution photographs or drawings were available upon which to identify visual and infrared correspondents.

The gross structure of the maps which bears obvious relation to the band structure, or at least which exhibits some nonradial bilateral symmetry about Jupiter's axis of rotation, seems to be of the same form but of a variable degree from map to map. Accordingly, it was felt that by superposing the maps on a grid whose mesh was commensurate with the spatial resolution and averaging the temperatures read at the points of intersection (the mathematical analog of composite photography), a map could be contoured which would (1) have a noise contribution lowered by a process the equivalent of signal integration but workable on nonstationary noise and yet (2) still possess real information, other than and in addition to limb-darkening, which would not be averaged out.

The result is shown in Figure 7. In the figure it is indeed true that structure exists whose lines of symmetry definitely favor the Jovian equator over the celestial equator. The correlation of the infrared and visible structure is somewhat ambiguous. The dark polar caps and the dark equatorial band appear to have common infrared radiative properties. This is manifested by the tendency of the outermost contours to pass within about the same distance of the polar and equatorial limb points. The tendency of the innermost contours to be flattened about the equator, rather than circular, implies that the two light bands in low latitudes are cooler radiators than the dark equatorial band. The wide separation between the 127.0° and the 127.5° contours in southern latitudes near zero longitude implies that the southern dark band is again warmer. This is also indicated by the outward curvature of the contours on the adjacent right, but the contours on the left do not duplicate this effect as they should if the band is to be interpreted as *generally* warmer. If the southernmost light band is cooler, the only obvious effect it displays is to flatten the southernmost contours near the pole, an effect which therefore ought to be absent near the north pole, as is observed to be the case. The light to dark band infrared contrast appears to be about 0.5°. If we fit a circle to the equatorial diameter of the 128.5° contour, its polar extremities fall on the 128° contour.

The northern light band presents a situation

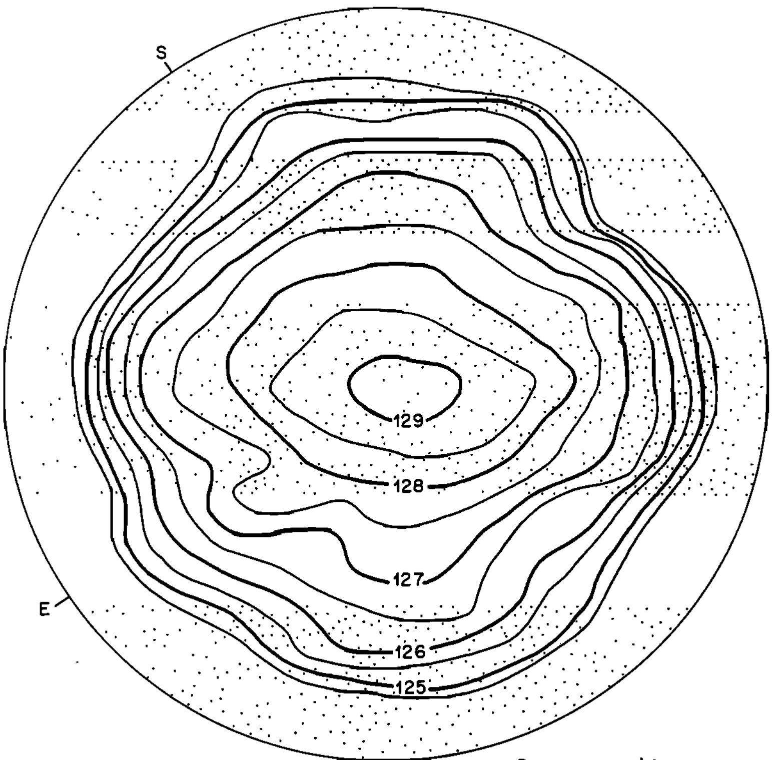

Fig. 7. Composite map of 8–14 μ brightness temperature distribution over the Jovian disk made by averaging Figures 1–5.

much more complex. It appears to be relatively hotter on the sunrise side and colder on the sunset side. It certainly does not fall into the hot-cold classification of, respectively, dark and light bands which has been discussed thus far. One conceivable theoretical mechanism for producing this result is a photochemical process in which the products are more opaque to 8–14 μ radiation than are the reactants and which requires a time to reach equilibrium of 2.5 hours or longer. We would thus see to deeper, hotter layers on the sunrise side than on the sunset side. On the other hand, we can ask why such a state is not more obvious in the visible. It is important to point out that some of these interpretational difficulties may hinge on the conceptual problem of defining 'gross band structure.' To illustrate this, a drawing of Jupiter made by Dragesco on December 7, 1963, is shown in Figure 8. It was the high-resolution visual picture of Jupiter which was closest in time of all available pictures to the epoch of the infrared investigations. The process of smearing information, both in the visible and infrared, may thus have consequences not totally accountable in the attempt to correlate results. This is made even more apparent by a close examination of Figure 6. In general terms, the right ascension scans indicate that the equatorial dark band is colder than the southern-adjacent light band, contrary to the indications of Figure 7. The declination scan in Figure 6, however, does indicate that the sunset side of the northern light band is cooler, as previously indicated. This partial enigma may also be related to the proximity of the GRS. It does not appear amenable to greater clarification at this time.

The most prominent feature of the maps is, as in paper 1, the general limb darkening, implying the increase of temperature with depth and therefore the existence of a green house mechanism. Such a conclusion is also indicated by the fact that the representative 8–14 μ

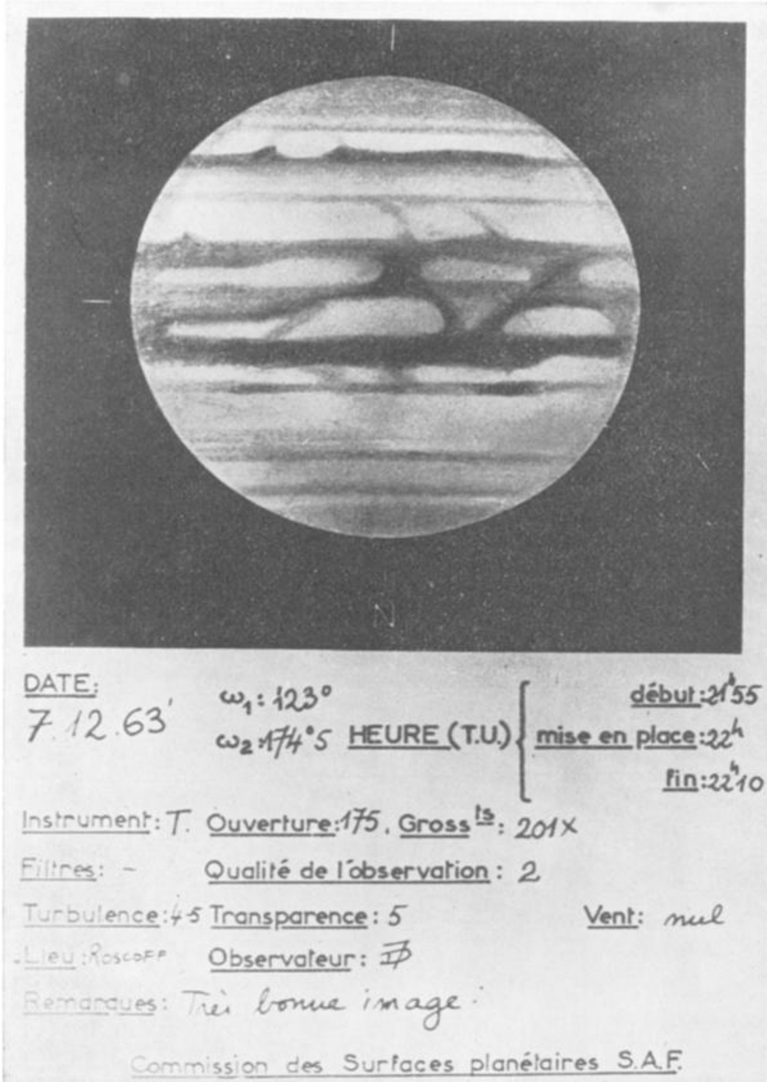

Fig. 8. Drawing by Dragesco of Jupiter's appearance five days before beginning the present infrared observations. Conceptual difficulties in interpretation of composite of Figure 7 are thus revealed.

brightness temperatures are much smaller than the 170° temperature inferred from the observed line ratios of the rotational transitions of the lower Jovian hydrogen molecules [*Zabriskie*, 1962]. See the letter in this issue of the Journal [*Wildey*, 1965] for an elaboration of theoretical implications.

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References

Murray, B. C., and R. L. Wildey, Stellar and planetary observations at 10 microns, *Astrophys. J.*, *137*, 692–693, 1963.

Murray, B. C., R. L. Wildey, and J. A. Westphal, Observations of Jupiter and the Galilean satellites at 10 microns, *Astrophys. J.*, *139*, 986–993, 1964.

Westphal, J. A., D. E. Martz, and B. C. Murray, An 8–14 micron infrared astronomical photometer, *Appl. Opt.*, *2*, 749–753, 1963.

Westphal, J. A., R. L. Wildey, and B. C. Murray, Infrared observations of Venus before the 1964 conjunction, *Astrophys. J.*, in press, 1965.

Wildey, Robert L., On the interpretation of thermal emission maps of Jupiter, *J. Geophys. Res.*, *70*(15), August 1, 1965.

Zabriskie, F. R., Hydrogen content of Jupiter's atmosphere, *Astron. J.*, *67*, 168–170, 1962.

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