NO. 181 A CORRELATION BETWEEN COLORS OF JOVIAN CLOUDS AND THEIR 5μ TEMPERATURES

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ABSTRACT

Observations of Jupiter at 5μ by Keay, Low, and Rieke were compared with color photographs by Minton and Kutoroff taken near the same epoch. A strong correlation is evident between the 5μ temperature distribution on the Jupiter disk and the cloud colors. Further comparison is made with photographs in the .888μ CH_4 absorption band. Strong correlations exist for features in System II latitudes at all three wavelegths but not for those that move with System I. This is attributed to more intensive convection in the Equatorial Zone. Owen's suggestion that colors may result from at least two mechanisms appears valid; a third appears responsible for blue features only.

1. Introduction

Observations of Jupiter at 5μ by Keay, *et al.* (1973) with the 61-inch telescope, in May 1972, revealed a considerable amount of thermal structure. Earlier observations, in April 1972, (Keay, *et al.* 1972) had been at lower resolution. A port diameter of 5.5 arc sec. was used for the April observations, reduced to 3 arc sec. for the May runs. In addition, the smaller port also defined the coordinates of recorded features with greater accuracy. Observations on May 20-22, 1972, at many Jovian longitudes, enabled these investigators to construct a cylindrical equal-area map of the entire planet. The reductions also disclosed the variation with distance from the Central Meridian (CM) of the heat flux.

2. Color Comparisons

Attempts by Dr. Keay and the author to correlate the 5μ features observed in April with features evident at photographic wavelengths were not successful. Photographs taken in blue, infrared, and methane-light were used for this comparison. However, attempts by Drs. Keay and Rieke to correlate the 5μ features observed in May with blue-light photographs met with some success. There is positional agreement between a 5μ depression and the Red Spot (RS), a group of 5μ sources and the South Temperate Belt (STeB); and between some 5μ depressions and light features in the Equatorial Zone (EZ). There was no obvious correlation between the 5μ features and their albedo in blue or infrared light.

However, when I compared the equal-area map with the 61-inch color photographs and with previous measures of features, a correlation between the Jovian colors and their 5μ brightness temperature (T_5) became evident. The RS and the NTeB are both orange-red (1972) and agree well in position with thermal depressions. Blue festoons in the EZ and two blue spots in the North Tropical Zone (NTrZ) agree well in position with areas of the greatest amount of 5μ radiation.

3. Position Measures and Map

The initial correlation warranted latitude and longitude measures of all visible features on our May 23 color photographs. Measures were made of these features on previous and subsequent dates, and drift rates were calculated. The positions of all features were reduced to the epoch of the 5μ observations and were plotted on the equal-area map. These measures ensured an objective analysis. An accurate comparison within the latitudes of +10° to -10° was only possible for features at System I longitudes of 170° to 330°. This region was photographed with the Catalina 61-inch reflector on May 23, 1972, at 0908 UT and 1047 UT by Mr. S. Kutoroff and the author. The remaining System I longitudes were photographed at dates found to be too distant in time for a comparison. This requirement was relaxed for features outside these latitudes for two reasons. The majority of belts and zones have few features, but those spots that were photographed drifted with a longer period and at a more predictable rate.

A table was prepared for each feature representing the area of that feature, its color, and the associated 5μ temperatures. If the feature lacked a distinguishable color, it was classified as either white or grey. This table depicts a temperature distribution for each visible-light feature.

4. Results

The areas of enhanced 5μ radiation are all associated with dark-brown or blue features. From +10° to - 10° latitude, some of the strongest 5μ sources coincide with blue sections of the North and South components of the EZ (EZn and EZs). The remaining strong sources almost invariably coincide with dark-brown sections of the EZn and EZs. At remaining latitudes, the two strong 5μ sources found near 130° and 170° longitude (System II) coincide closely in latitude and longitude with two distinct blue spots near the center of the NTrZ. Other sources were located along the STeB and near the NNTeB, with the stronger sources coinciding with the darker-brown regions of these belts.

The areas of weak 5μ radiation (depressions) tend to cluster in latitude. The thermal depression near +20° to +35° latitude has the greatest continuous extent in longitude. This area is occupied by the NTeB and the NTeZ, with the NTeB in better positional agreement at more longitudes than the NTeZ. The NTeB is orange-red in color. A thermal depression is evident from -18° to -24° latitude, and 357° to 8° longitude (System II) This may be compared with visible-light measures (reduced to May 21) of the RS, whose boundaries are -17.°5 to -28.°0 latitude, and 352° to 12° longitude. It is significant that the 5μ dimensions are distinctly smaller. The RS was orange-red in color. The thermal depressions within -10° to -25° are almost totally within the expanse of the North and South components of the South Equatorial Belt (SEBn and SEBs). These normally dark components are presently bright, and this entire region (-10.°0 to -20.°3) is light-salmon in color. From +10° to -10° latitude, the thermal depressions tend to coincide with irregularly-shaped yellow features. Figure 1 shows the relation between color and temperature measures at 5μ.

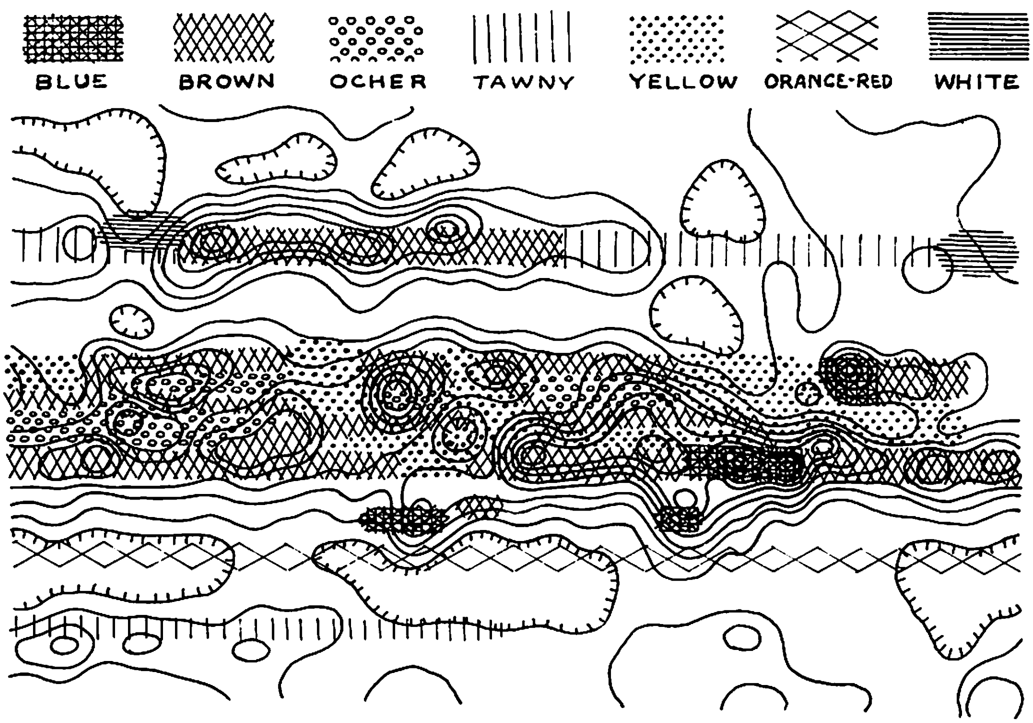

Fig. 1 Visible colors from color photos of May 23, 1972 vs. surface distribution of 5μ temperatures obtained May 20-22

The regions of Jupiter which lack both prominent 5μ sources and thermal depressions tend to be either *white zones* (or spots) or *grey regions*. Grey regions include both dusky zones and faint belts. No obvious difference exists between white and grey features with respect to their 5μ temperatures. Nor is a close correlation evident between the type of feature (spot, belt, or zone) and its T_5.

However, a relation does exist between all distinguishable Jovian colored features and their associated values of T_5. This is shown in Figure 2 which depicts the percentage of area (within the area surveyed) of each color as a function of T_5. For reasons mentioned previously, different types of features were consolidated by color, and white and grey features were combined. As T_5 increases, there is a progressive change in the associated color of that feature from yellow or orange-red to blue. Figure 2 also shows that as T_5 increases, the transition in color becomes more abrupt. That part of the graph for System I applies to areas within +10° to -10° Zenographic latitude and 170° to 330° longitude, and represents 7% of the Jovian surface. The part for System II applies to all remaining latitudes and longitudes, and represents 85% of the Jovian surface.

5. Interpretation

Although these relations are based on May 1972 observations only, those found for System II may be more generally representative. The area surveyed is large and not presently (1972) unusual in appearance. However, the characteristics of features within the domain of System I have recently changed. Following the outbreak of two SEB disturbances in 1971, the EZ has become considerably more reddish-yellow in color; and brighter in methane-light photographs (Minton 1973*a*). This unusual circumstance and the smaller area surveyed, suggest that this relation may not be representative of the long-term aspect. However, the dark, wedge-shaped area, reported by Westphal (1969) to produce the highest flux recorded, was identified on LPL color films of May 14, 1969, as a *blue festoon*.

Danielson and Tomasko (1969) propose a two-layer model of Jupiter to reconcile spectrographic and bolometric temperature observations. In this model, there exists an upper cloud deck at a temperature of 145°K which has a transmission of about 0.5. The lower deck would be near 219°K and have a large optical depth. Based on much spectroscopic evidence, they suggest that the upper cloud is composed of NH_3 ice, and, following the analysis of Lewis (1969), they suggest that the lower clouds are

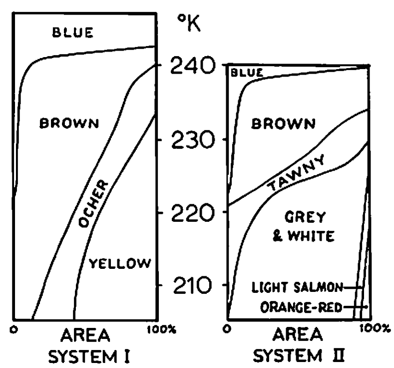

Fig. 2 Color distribution vs. 5μ temperatures by area, separately for System I and II regions

composed of NH_4HS and H_2O ice. In the two-layer model, light returned from the upper deck would give Jupiter characteristics of a reflecting model; and from the lower deck, that of a scattering model. Lewis and Prinn (1970) propose that in the lower deck, H_2S may be responsible for the observed colors. Brought up from unobservable depths, this gas would dissociate into H and HS by solar UV (.220-.270μ), penetrating through breaks in clouds and, to some extent, through the upper NH_3 cirrus deck. Lewis and Prinn indicate that .220-.270μ radiation is not absorbed by H_2, He, and CH_4, somewhat by NH_3 and considerably by H_2S. They determine the amount of Rayleigh scattering at these wavelengths based on a cloud-free, molecular (H_2, He) atmosphere. They show that recombination of H and HS would produce hydrogen polysulfides, ammonium polysulfides, and sulfur. These are yellow, orange, and brown in color. Owen and Mason (1969) suggest that sulfur compounds may be responsible for only part of the observed cloud colors, and that organic polymers may play a major role. Since the Lewis-Prinn theory applies to the Jovian colors at the lowest observable levels, Owen and Westphal (1972) suggest that solar UV may be responsible for the color of the highest features. Therefore, we have two somewhat discordant hypotheses that ultraviolet light is ultimately responsible for the observed colors of the highest *and* lowest Jovian features. Direct observation of cloud altitudes is therefore important.

I have compared the appearance of Jupiter in the .888μ CH_4 band with the colors and intensities of features at coincident positions from 1968-69 through 1972 (Minton 1973*a*). I find no simple correlation between the colors of all the features and their intensity in this band (color vs. CH_4), nor one between the intensities at visible wavelengths and their intensity in this band (V vs. CH_4). The intensity in the CH_4 band should be a fair approximation of relative altitudes, if only for a limited vertical range. Scattering at .888μ is not as strong as it is at shorter wavelengths. Belts and zones show considerably more contrast at this wavelength than in the UV near 0.32μ, and there is no evidence of limb brightening near quadrature as there is at UV and blue wavelengths. In view of the good correlation between the color of a feature and its associated 5μ temperature (color vs. T_5), it is surprising that there is not an equally good correlation between the color of a feature and its intensity in the .888μ CH_4 band, since there is overwhelming evidence that temperatures increase with depth. However, when features within the domain of System I boundaries (+10° to -10°) are omitted in these comparisons, a good color vs. CH_4 correlation is obtained for the abovementioned four apparitions, while there is still no obvious V vs. CH_4 correlation. Evidence for the good color-vs.-CH_4 correlation is based on the following observations. During this period, the RS was always orange-red in color and always bright in methane light. From 1971 through 1972, the NTeB was orange-red in color and bright in methane light. Prior to this, it was split and faint; and was also faint in methane light. In 1969-70 when the NTrZ became light red in color, it became bright in methane light. Prior to this, it was white; but not exceptionally prominent in methane light. No exceptions in this trend were evident in System II. The lack of a marked blue vs. dark-in-CH_4 trend is related to the lack of blue features in the area of System II, and the great strength (small penetration) of the CH_4 band. It is provisionally concluded that *the positive correlation between orange-red color and elevation in the System II areas is related to the greater stability there, giving time for the solar UV exposures discussed by Lewis and Prinn to run their course.* In the Equatorial (System I) Zone the time scales of the clouds observed are on the whole shorter, possibly inadequate for the photochemical processes to reach near-equilibrium. The Lewis-Prinn computations indicate that the critical period dividing the two regions may be of the order of some weeks.

Although there appears to be no general correlation between the visual intensity of a zone and its intensity in the CH_4 band, the latitudes of the bright CH_4 zones do coincide with the latitudes of some visible-light zones or orange-red features. The only exceptions are features within the System I area and the South Polar Hood. However, UV photographs of the SPH suggest that it has scattering properties unlike the surrounding South Polar Region (Owen and Mason 1969). The latitude of the North edge of the SPH varies in accord with the amount of insolation, which suggests that this haze cap is more volatile than the intermediate latitude zones (Minton 1973).

Owen (1972), in summarizing much spectroscopic evidence, points out that there appears to be no increase in the effective absorbing path in NH_3 and CH_4 over the dark areas emitting strongly at 5μ. This needs verification with high spatial resolution. The 5μ sources predominantly occur in the System I area. Molecular absorption differences are found within System II latitudes (Gehrels, *et al.* 1969), (Owen, Mason 1969), (Moroz, Cruikshank 1969). Gaseous NH_3, CH_4, H_2 and He are nearly transparent at 5μ, leaving the opaque clouds as the principal sources of radiation. Westphal (1969) suggests that the hot sources may coincide with either partially-transparent regions or breaks in the cloud deck. Danielson and Tomasko (1969) based their model on the first possibility. Keay *et al.* (1972) suggest that if the sources could be identified with visible features, the latter interpretation would be greatly supported. It is significant that in 1969 and 1972, *no* 5μ sources were found to be coincident with white, grey, orange-red, or light-red features. Features with these colors move predominantly in System II. This is strong evidence that these cloud layers block 5μ radiation from the hotter layers beneath.

The characteristics of Jupiter at the various latitudes (thermal outflux, rotation periods, molecular absorptions, periodic disturbances, feature longevity) suggest that large features within the System I area have more nearly equal altitudes than those in System II. This may be due to greater vertical mixing in System I caused by the greater thermal outflux there. In System II, thermal sources are generally coincident with breaks in a higher cloud cover; in System I there is more of a mixture of hot and cold features. Kuiper (1972) attributes periodic disturbances (SEB, STrZ), and long-enduring spots (RS, STeZ white ovals) to the sudden or gradual relaxation of low-altitude inversions. He cites the lack of long-lived oval clouds close to the equator as an indication that Coriolis force is an active ingredient of cloud dynamics at other latitudes. An additional factor may be that in System I the greater outflux produces more vertical convection which prevents establishment of an inversion. As stated above, this more intensive convection near the equator will also shorten the time scales of UV exposures and thereby affect the cloud colors.

It is important to differentiate between the two classes of "warm" colors observed in System II. Features with light-red to orange-red colors appear to be cool at 5μ, and bright in methane-light photographs. Features of tawny (light-brown) to brown-red colors tend to be 5μ sources of varying temperatures, and are dark in CH_4. This second group would include those colors Lewis and Prinn attribute to sulfur and its complex forms. The greater longevity of most System II features would favor any UV-induced color change, assuming other conditions (altitude, composition) were met.

The blue features observed in 1969 and 1972 to be among the *strongest 5μ sources* were festoons and two NTrZ spots. Their 5μ temperatures were greater than or equal to the boiling point of NH_3 at 1 atm. of pressure. It is tempting to attribute the blue color to Rayleigh scattering in a predominantly gaseous cloud. The motions of blue festoons are not well documented in the literature, but are being investigated. The motions of blue spots in System II suggest that they are discrete spots, i.e., opaque clouds - not vents or holes in a lower deck. This interpretation obviously contradicts the proposal that sources coincide with cloud breaks in System II, but it should be emphasized that the remaining System II sources (STeB, NNTeB) are much longer-enduring features. In all probability, they are in closer thermal equilibrium with the surrounding atmosphere.

The lifetimes of blue spots in System II appear to be significantly longer than those (festoons) in System I. The two NTrZ blue spots were evident for the entire 1972 apparition. This is fairly typical for other blue spots in System II at previous apparitions. *The lifetimes of the two festoons* in Figure 2 were one and two months. This appears to be a typical lifetime for a festoon. Prior to being blue, these two areas were dark-brown sections of the EZn and EZs. They reverted to their former color with the disappearance of the blue color.

The 5μ temperatures determined for the remaining strong sources appear to be high enough for most proposed cloud constituents to exist in liquid phase or liquid solutions. The influence of this on the Lewis and Prinn hypothesis for colors observed in the lower deck is uncertain. The proposed vertical mixing in System I may not allow the required time scale for a slow color-producing mechanism. The observed color changes of the highest features suggests depletion of ultraviolet light already at the highest altitudes. *White zones and spots with long lifetimes*, and at presumably intermediate altitudes (System II latitudes) *have not turned light-red or orange-red.* This would indicate that other effects are operative at the deeper layers to produce orange colors.

The temperatures of the coldest features are significantly higher than those determined spectrographically, 210°K vs. 145°K. It will be important in the future to obtain accurate temperature measures of the coldest regions, even at the expense of resolution since values near 200°K are close to the limit of sensitivity at 5μ. Except for blue features, the interpretations here presented are not based on absolute values of temperatures. The hottest and coldest regions are well identified, and relative temperatures are well determined. These observations indicate that regardless of the composition of the hottest features, their observed colors are temperature-dependent.

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