Whistler emission, which is interpreted as lightning whistlers from the Jovian atmosphere.

Extensive radio spectral arcs (~ 1 to > 30 MHz), occurring in patterns correlated with Jovian longitude.

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10. The extraordinary scientific findings discussed in this issue of *Science* represent the culmination of many years of dedicated, tireless effort by a large number of people at all levels in numerous organizations. The scientists associated with the Voyager Project gratefully acknowledge the superb accomplishments of all these individuals. The Voyager Program is part of NASA's Office of Space Science, Lunar and Planetary Exploration Program. The Voyager Project is managed by the Jet Propulsion Laboratory of the California Institute of Technology under NASA contract NAS 7-100.

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Summary of Historical Data: Interpretation of the Pioneer and Voyager Cloud Configurations in a Time-Dependent Framework

Abstract. *Ground-based imaging of Jupiter at visible and infrared wavelengths has been used to build up a time sequence of cloud feature variations. The global cloud configuration seen by Voyager 1 appears markedly different than that seen by Pioneer 10 and 11. In the context of historical data, these two different cloud distributions are not unique but part of a continuous spectrum of global variations. The most recent global changes occurred in a pattern which has been a characteristic trend observed many times before.*

Jupiter has long been known to display large-scale variations in its visible appearance. The Voyager 1 encounter with Jupiter was, in effect, a snapshot of a planet constantly changing from one global cloud configuration to another. In this report we attempt to put this brief view into the historical perspective of what was known previously from ground-based monitoring at visible and infrared wavelengths. We will also describe the data base and preparation which went into the target selection for the Voyager imaging and infrared radiation (IRIS) experiments.

Designed into the Voyager 1 Jupiter encounter was a capability for targeting experiments to specific regions of high scientific interest. A Target Selection Working Group (*1*) was organized to designate the regions to be targeted. Generally, targeting consisted of two tasks. First, specific features were selected as targets and, second, accurate predictions were made of the temporal stability of features and their position at the time of encounter. Because of Jupiter's dynamic atmosphere and the constraint that the final targeting input deadline was 1 month before encounter, this second task demanded a large effort. A coordinated program to integrate ground-based observations in the visible and 5-μm wavelengths was carried out during the past year (*2*), resulting in prediction maps showing the location of desirable features.

Jupiter's appearance in visible as well as 5-μm wavelengths has undergone several large-scale changes since the Pioneer 10 encounter (December 1973). We will relate these changes, in the context of historical observations (*3*), to the long-term dynamical aspects of the planet. We will discuss zonal cloud cover as well as specific morphology. For a more complete description of Jovian historical cloud morphology, see (*3*).

Variations in the visible. A comparison of cloud configurations of Jupiter at the time of Pioneer 11 (*4*) and Voyager 1 is shown in Fig. 1. The most obvious changes are the darkening of the South Equatorial Belt (SEB) surrounding the northern edge of the Great Red Spot (GRS) and the brightening of the region between 23° and 35°N zenographic latitude. During the past 75 years, albedo changes of this magnitude have occurred at intervals of 5 to 8 years, with recurrence of both the Pioneer and Voyager aspect. The manner in which the high albedo regions form and dissipate and the cloud-top temperatures derived from 5-μm imaging data (*5*) indicate the high albedo regions are clouds at a higher elevation which obscure the lower cloud decks.

Yearly comparisons of Jupiter photographs indicate that between 1973 and 1974 the positions of the most prominent belts and zones remained unchanged and the only color difference was the subtle loss (in 1974) of blue-gray color in the equatorial edge of the SEB. In 1975, the dark southern component of the SEB at about 12°S appeared in what was a very broad and featureless South Tropical Zone (STrZ). The area between the northern and southern components of the SEB to the east of the GRS appeared white and featureless, that is, zonelike. However, to the west of the GRS this same latitudinal band was dark gray in color and mottled. This appearance was part of a characteristic trend known as the SEB disturbance and has been observed many times before (*3*, *6*). The South Temperate Belt (STeB) at about 38°S, which was longitudinally homogeneous in 1973 and 1974, appeared to have broken up into small fragments in the 1975 apparition. Other changes apparent in 1975 were that the equatorward edge of the SEB regained its blue-gray color and the north edge of the North Equatorial Belt (NEB) acquired a conspicuous dark brown color. In 1976, the SEB disturbance completely obliterated the zone (that is, the STrZ) separating its northern and southern components. This very wide belt appears blue-gray on its north edge and brown to the south. The GRS lost most of its contrast because of its proximity to dark material surrounding the red spot and to a belt directly to the north. The NEB remained unchanged from the previous year but the STeB once again displayed a homogeneous appearance. In the period between 1976 to the present, Jupiter has displayed only very minor albedo variations. These changes were mainly a whitening of the STrZ into a very broad region between 17° and 35°N, and some small color differences in the region from the equator to 38°S.

In summary, the past 6 years of Jovian cloud activity have been characterized by color variations in all belts and by a major SEB disturbance resulting in the darkening of a large part of the STrZ.

Five-micrometer features. Yearly monitoring of Jupiter in the 5-μm window has been taking place from the Palomar 5-m telescope since 1973 (*7*). In this wavelength region, the Jovian atmosphere is relatively free of gaseous absorbers and high flux contrasts observed are indicative of variations in cloud height. Generally, the hottest regions at 5 μm, and therefore most free of high clouds, correspond to the blue-gray areas in some Jovian belts. Brown belt regions are of intermediate brightness temperature and the white zones and GRS are the coldest areas (*5*). One of the specific Voyager goals was to point the IRIS experiment into one of the hottest 5-μm regions. This would ensure measurement of the deepest observationally accessible levels in the Jovian atmosphere.

The rather dramatic changes in Jupiter's physical appearance at visible wavelengths have been manifested in the 5-μm appearance of the planet as well. Figure 2 shows four 5-μm images acquired in September 1973, August 1974, September 1975, and October 1976, respectively. The difference between the 1973 and 1974 apparitions is shown in Fig. 2, a and b. Jupiter's 5-μm appearance changed from a symmetric equatorial belt configuration to one in which the NEB is much more prominent than its southern counterpart. This is a result of a decrease in the 5-μm flux emitted from the SEB to 35 percent of the value observed in 1973. The area affected by this flux decrease corresponds to the same latitudinal region which changed color from blue-gray to brown in visible photographs. Five-micrometer emission from the SEB increased again in 1975 and once again equaled or surpassed the emission from the NEB (Fig. 2c). Less intense levels of emission may be seen in the otherwise cold STrZ. These areas correspond to dark features on visible photographs and seem to be related to the start of the SEB disturbance. In Fig. 2d, from 1976, the SEB was continuous and bright at 5 μm. The brightest features, in this view, are the equatorward components of the NEB and SEB, which are of roughly equal intensity. The GRS, which normally does not appear in 5-μm images, is visible in the lower left as a dark area because it is surrounded by hot features. During the time between the 1976 apparition and Voyager 1 encounter, the general 5-μm aspect of the SEB changed by a clouding over of the equatorward component and a brightening of the southern component. Figure 3 shows a comparison of morphological features between the 5-μm data and a Voyager image.

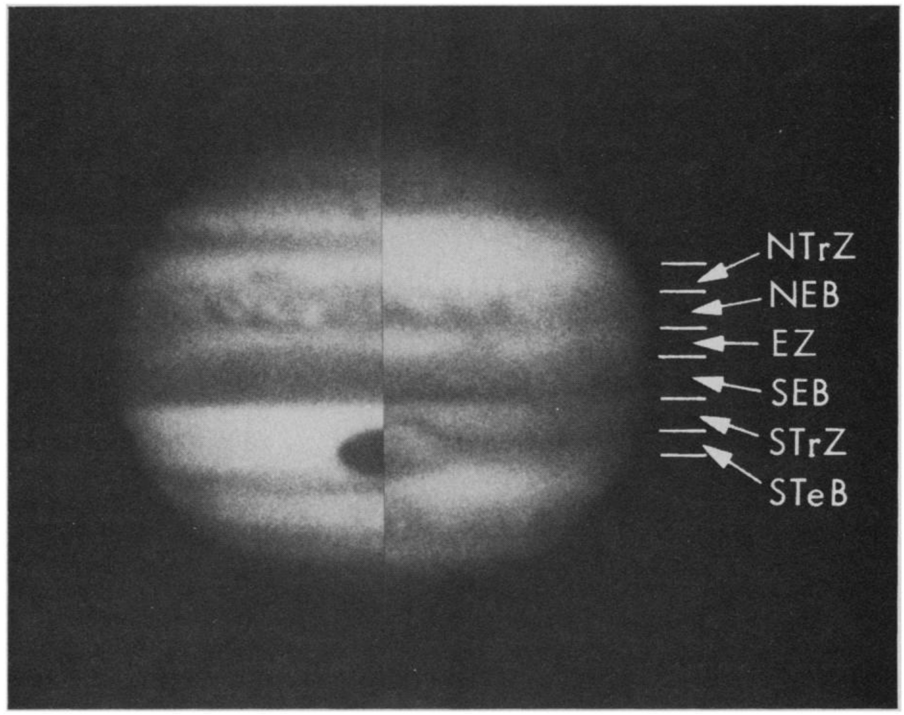

Fig. 1. A composite image composed of two ground-based images obtained on 8 August 1974 on the left and on 11 February 1979 on the right. Both images were photographed on III-0 emulsion with no filter. This composite image demonstrates the difference in albedos in blue light at the time of Pioneer and Voyager encounter (New Mexico State Observatory). Shown at the right are some of the most prominent regions, the equatorial zone (*EZ*), north and south equatorial belts (*NEB* and *SEB*), north and south tropical zones (*NTrZ* and *STrZ*), and the south temperate belt (*STeB*).

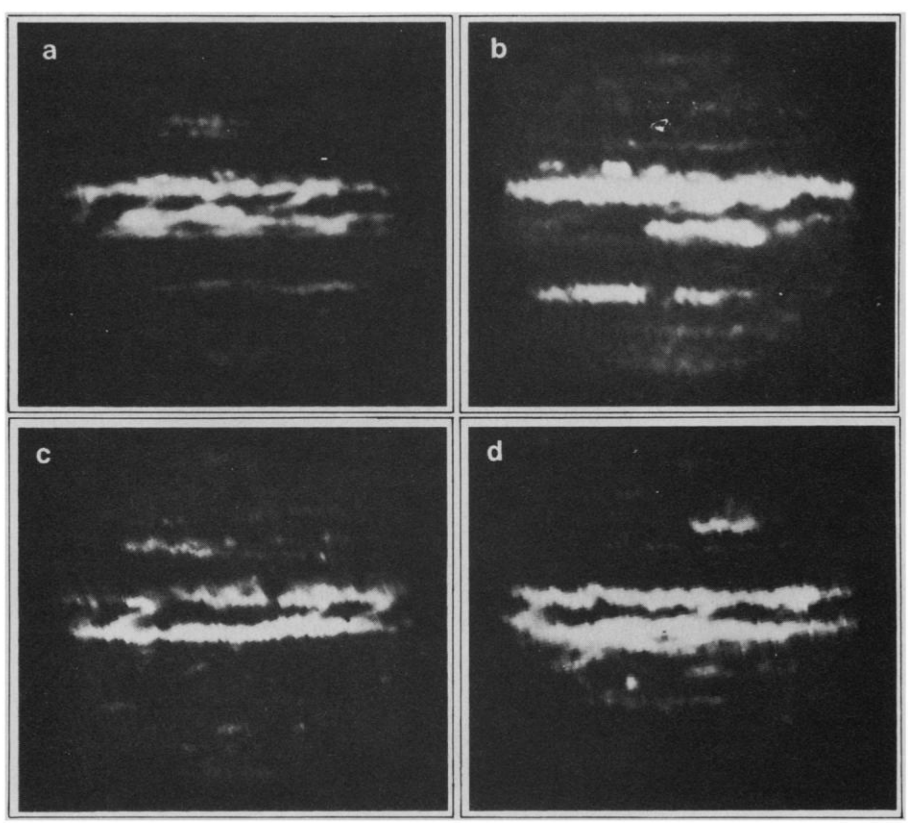

Fig. 2. Yearly comparisons of Jupiter at 5 μm from 1973 to 1976 illustrating the global cloud variations. The data in (a) to (d) were recorded on 20 September 1973, 21 August 1974, 25 September 1975, and 5 October 1976, respectively, at the 5-m telescope at Palomar Observatory, Flagstaff, Arizona. The GRS is on the disk in all images but is only visible as a dark feature in (d). North is at the top and east at the right.

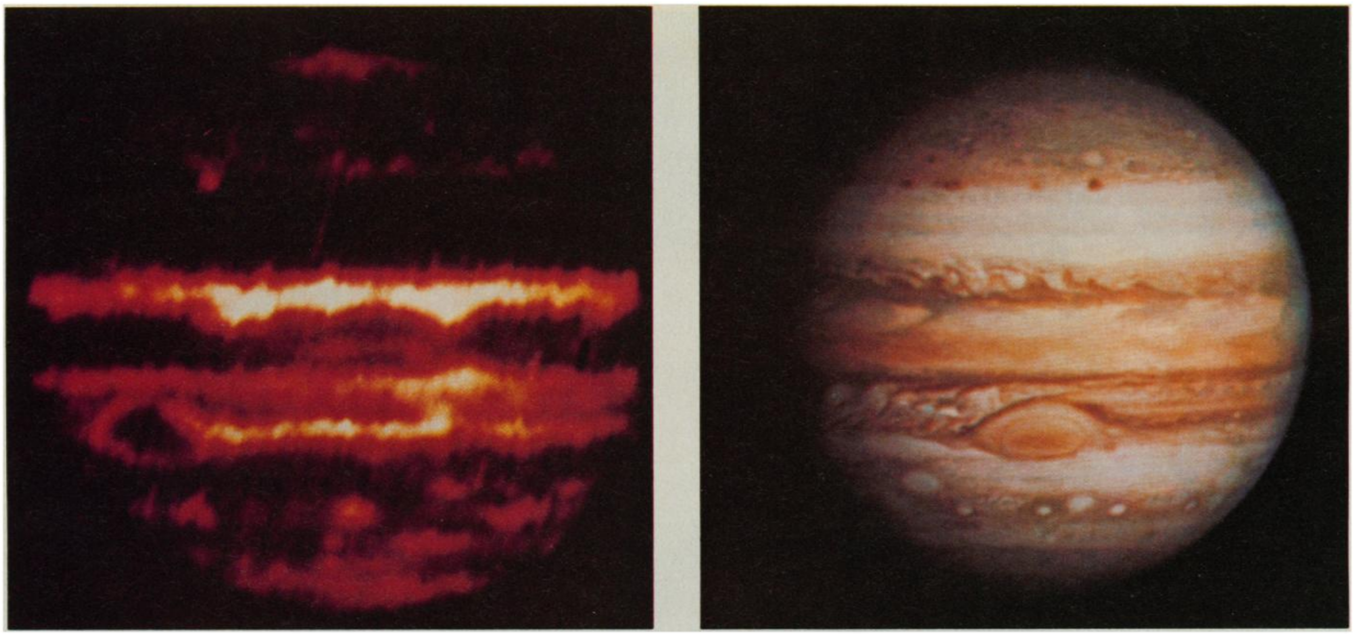

Fig. 3. A comparison of a 5-μm image of Jupiter (left), recorded at Palomar on 10 January 1979, and a Voyager 1 image (right) recorded 1 hour later. The 5-μm image is shown in false color where bright areas are hot. The Voyager 1 image taken at a distance of 535×10^6 l, was constructed from three black-and-white images in three colors. The hottest features at 5 μm correspond to the blue-gray areas in the NEB. The GRS can be seen as a cold region surrounded by warm areas. White zones are featureless and cold at 5 μm.

Historically, rotational velocities have been derived by determining the drift rates of cloud systems which are large enough to be resolved on ground-based photographs. This constraint has yielded data of apparent cloud motions derived from features with diameters 3000 km or greater and, hence, has raised questions concerning velocities as a function of height, the constancy of occasionally observed currents, and the inability to determine whether phase velocity or mass motion is being observed at various locations on the planet. Detailed measurements have been carried out at New Mexico State University since early 1974 and tabulations of the velocities of various features are available (*8*). Here we will summarize some of the variations that have occurred since Pioneer 11.

The white material located to the west of the GRS in the Voyager images (Fig. 3) is related to the SEB disturbance that began on 2 July 1975. Until that time, the aspect of the region from 10° to 23°S remained as it appeared during the Pioneer flybys. On that date, however, an intensely bright white cloud appeared at 89.2° longitude and 17°S. By mid-August, three other longitudinal regions had become active, causing a general darkening of the region. Material appearing at 17°S is drawn into the prograde current at 13°S and into the retrograde current at 18°S causing the bright material to be drawn out into S-shapes which drift toward the GRS at approximately 1.4° per day. As these features approach the GRS, their forward motion stagnates, leading to the development of the bright turbulent region to the west of the GRS. Historically, this region to the west of the GRS has displayed a wide range of behavior from being completely obscured by a bright cloud deck at the time of Pioneer observations, to displaying no cloud pattern at all in late 1964, even though the SEB appeared dark and homogeneous at that time. During the past 15 years, there have been three major periods of activity in this region, 1965 to 1969, 1971, and 1975 to the present. The period from 1967 to 1969 resembled the current configuration, while the 1971 event, on approaching the GRS, spilled over into the equatorial region and dissipated quickly (*6*). Historical records do not indicate a seasonal relationship; however, there is evidence that the manner in which an SEB disturbance develops is influenced by conditions in the southern edge of the equatorial zone.

Three white ovals about 14,000 km long are located in a region south of the GRS at 33°S. These features were observed to form as remnants of a general brightening of the region in 1938. Since that time, both the length and velocity of the features have decreased. The velocity of the individual ovals vary; hence, distances of separation change as a function of time. In mid-1975, a bright cloud feature formed between two of the ovals. Although the separation between these two ovals has increased from about 50° in 1974 to about 80° at the time of Voyager, this feature, seen in Fig. 3 to the east of the GRS with a white oval below the GRS, has not dissipated. Since the ovals drift at more than one-half of a degree per day relative to the GRS, the configuration below the spot should change considerably before closest approach of Voyager 2 on 9 July 1979.

A series of small white ovals surrounded by low albedo regions are located at 41°S and can be seen in Fig. 3. Infrared 5-μm images indicate that these white ovals are high clouds surrounded by warm lower clouds (*5*). Spaced roughly 25° apart, these features appear to drift as a system in a linear manner at 7 m/sec. Features of this type are typical of this latitudinal region; however, a variable longitudinal expanse has appeared to be obscured by an overlying bright cloud in the interval between Pioneer and Voyager.

In the northern hemisphere, the small brown spots are typical of the region near 35°N and are occasionally seen as hot 5-μm features (Fig. 3). To the south at 31°N, similar features moving in a retrograde direction are frequently present; however, the growth of the high albedo cloud deck in this region has obscured details at this latitude.

The midlatitudinal region, extending from 10° to 25° in latitude, contains a wide variety of relatively short-lived cloud features. During the Pioneer encounter, a miniature red spot was visible at 15°N, which subsequently faded and became indistinct. In September 1975, two bright white clouds emerged in the high-velocity jet located at 23°N. These features had eastward velocities of 169 m/sec and circled the planet before dissipating. This was accompanied by an increased drift of 1.5 to 10.0 m/sec, in other features at 15° to 18°N.

The Voyager images show a wedge-shaped turbulent pattern emerging from the southern edge of the North Tropical Zone (NTrZ) and extending equatorward (Fig. 3). Since this pattern is confined in longitude, it is tempting to consider that this feature may be induced by the influence of the GRS. This is not the case, however, since this pattern is observed to drift 0.46°S per day, and in 1977 to 1978 two wedge-shaped systems were present. By August of 1978, one system had dissipated leaving the present pattern with the southern edge of the NTrZ contracted northward to 19° latitude. When this is the case, dark brown clouds similar to those seen in the Voyager data have been present. During periods when the belts near 30° and 35°N are wider, similar low albedo features also appear in this region. Dark brown clouds correspond to enhanced regions of 5-μm emission, indicating a relative absence of high zonal clouds.

Inspection of the equatorial zone of the Voyager data indicates several plumes similar to those reported by Pioneer investigators. At the time of Pioneer 10 and 11, the plumes were well developed and drifting at a rate of 4 to 6 m/sec relative to the mean motion of the dark gray features between the bright areas. Since the beginning of 1975, the velocity of the plumes has slowed to approximately that of the surrounding features; hence, their distinctive character has diminished, making continuous trackings difficult.

This study serves to introduce ground-based data concerning the morphology, origin, longevity, and long-term drift rates of cloud features, and to indicate how this material is being integrated with Voyager data.

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2. Photographic data were provided by New Mexico State University and Lowell Observatory, and 5-μm imaging was acquired at Palomar and Mauna Kea observatories [see R. J. Terrile *et al.*, *Science* **204**, 1007 (1979)]. Data from the observatory phase of the Voyager Mission were also used in targeting.
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The Jupiter System Through the Eyes of Voyager 1

Abstract. *The cameras aboard Voyager 1 have provided a closeup view of the Jupiter system, revealing heretofore unknown characteristics and phenomena associated with the planet's atmosphere and the surfaces of its five major satellites. On Jupiter itself, atmospheric motions—the interaction of cloud systems—display complex vorticity. On its dark side, lightning and auroras are observed. A ring was discovered surrounding Jupiter. The satellite surfaces display dramatic differences including extensive active volcanism on Io, complex tectonism on Ganymede and possibly Europa, and flattened remnants of enormous impact features on Callisto.*

In a flurry of observational activity, Voyager 1 arrived at the planet Jupiter on 5 March 1979. One hundred days earlier, however, the resolution of Voyager cameras (*1*) had already exceeded the best resolution available from ground-based telescopes. About 30 days before encounter, their resolution and image quality were comparable to those of the best Pioneer 10 and 11 images. The effective resolutions at encounter for Jupiter and three of the four Galilean satellites (Io, Ganymede, and Callisto) were only a few kilometers. This improvement in resolution is comparable to the transition from naked-eye observations of Earth's moon to the best ground-based telescopic photographs. Comparable improvements have been achieved in time resolution—that is, in the frequency and regularity with which observations are made.

The approximately 18,000 photographs taken by Voyager 1 in the Jupiter system have led to many new data products and scientific findings, including color motion pictures of the dynamics of the Jovian clouds; images of Jovian lightning and auroras; and the discoveries of a Jupiter ring system, of the elongate shape of Amalthea, of a major system of active volcanoes and substantial recent surface modification of Io, and of novel fracture systems and presumptive tectonic activity on Ganymede and Europa.

The atmospheric dynamics, reducing atmospheres, icy satellites, rings, and other features of the Jovian system give it an environment very different from that of the terrestrial planets with which we have now become familiar. The bodies in the Jupiter system explored by Voyager 1 do not resemble closely either the planets in the inner solar system or one another. The wide range of unexpected findings is due both to the real differences between the outer and the inner solar system and to the depth of our prior ignorance, caused in part by the 4 astronomical units (AU) that separate Earth and Jupiter. The sense of novelty would probably not have been greater had we explored a different solar system. It seems clear that analyses of Voyager 1 data and of data to be acquired by the Voyager 2 and Galileo spacecraft will provide major insights into the origin and evolution of the solar system and, through comparative planetology, of our own planet.

Jupiter: Global atmospheric structure. To obtain the best space-time color coverage of Jupiter's changing atmosphere during Voyager's approach and encounter, several observational strategies were followed (*2*). From 60 to 12 days before encounter (E − 60^d to E − 12^d), multicolor images were taken every 72° of longitude (one-fifth of a Jovian rotation) (*3*). Resolution ranges from 1200 down to 240 km per line pair (lp) for the last systematically scheduled whole-disk mosaics (*4*). Approximately 9300 single-color images were obtained during this period.

From E − 12^d until encounter, Jupiter was too close to be covered by mosaics of reasonable size, and it was necessary to selectively target various patterns of images for specific features. Because of the complexity of the spacecraft com-

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