METEOROLOGY OF THE OUTER PLANETS

Garry E. Hunt
Laboratory for Planetary Atmospheres
Department of Physics and Astronomy
University College London
London WC1E 6BT

INTRODUCTION

One of the fundamental problems in atmospheric physics is concerned with providing improved weather forecasts for the Earth and predicting the future climate of our planet. However, this is a particularly difficult task since the meteorology of the Earth is affected by a wide range of physical factors – clouds, oceans, continents, polar caps, deserts and forests – all of which respond differently to the solar energy which drives the weather systems. In addition, external factors, such as the changing energy from the sun, are thought to strongly influence the Earth's meteorology. To provide a broader understanding of atmospheric phenomena, detailed studies of planetary atmospheres have been conducted, since they provide a unique opportunity to investigate these basic problems in fluid dynamics under boundary conditions which are quite different from those found on the Earth.

The giant outer planets provide, at first sight, a more varied set of objects, since they are huge, rapidly rotating, low density planets with optically reducing atmospheres (Belton (1981), Goody (1981), Kondratyev and Hunt (1981)). The giant planets Jupiter, Saturn and Neptune possess internal heat sources (MacFarlane and Hubbard (1981)) while the present observations of Uranus suggest that it may be in radiative equilibrium. The effects of internal heating as an additional driving mechanism to differential solar heating for a planetary atmosphere are not fully understood.

In order to provide insight into this fundamental problem, we discuss in this paper the meteorologies of the atmospheres of the major planets. The detailed observations of Jupiter and Saturn by the Pioneer 11 and Voyager spacecraft now make it possible to provide quantitative discussions of the motions of these planetary

atmospheres (see, for example, Hunt (1981)). We therefore first
review our basic knowledge of Jupiter and Saturn and then discuss
our current understanding of Uranus and Neptune.

THE METEOROLOGIES OF JUPITER AND SATURN

For more than 300 years, observations of large-scale cloud
features have provided the basic information on the gross
characteristics of the atmospheres of Jupiter and Saturn (see, for
example, Peek (1958), Alexander (1962) and Smith and Hunt (1976)).
The visible appearance of Jupiter is one of alternating cloud bands
of differing colours separated by jet streams. Superimposed upon
these cloud systems are large-scale features, such as the Great Red
Spot and the three white ovals, which appear to have lifetimes
varying from decades to centuries (Smith et al(1979a,b)). Saturn
is in some ways similar to Jupiter. Although the banded structure
is clearly seen, there is a marked hemispherical asymmetry in the
clarity of the visible features due to possible seasonal changes in
the upper atmospheric haze layers. Furthermore, there are
considerably less large-scale cloud features to be seen in the
Saturnian atmosphere (Smith et al (1981)).

On a large scale, there is little, if any, pole to equator — *wait*

Unlike the meteorological systems of the terrestrial planets,
the weather systems of these planets are not solely driven by
differential solar heating, since they both possess strong internal
heat sources. Jupiter emits 1.67 ± 0.13 times the energy it
receives from the sun, while the equivalent factor for Saturn is
$\sim 2.8 \pm 0.9$. Consequently, the meteorologies of these planets are
influenced by the two energy sources and by the strong rotation.
All the cloud velocities on Jupiter are referenced to the System III
period of $9^h 55^m 29.711^s$ and on Saturn to the System III period of
$10^h 39.9 \pm 0.5^m$.

On a large scale, there is little, if any, pole to equator
energy transfer at the level of the visible clouds, which is a
major difference between the Earth and the giant planets. The
Pioneer 11 measurements of Ingersoll et al (1976) have shown that
on Jupiter the difference between the equator and pole temperatures
is no more than 3K. The belt/zone structure terminates at $\pm 45^o$.

Although Saturn possesses similarly small temperature gradients, at the time of the Voyager encounter the temperatures at the 209mb level were noticeably warmer in the southern, compared with the northern, hemisphere of the planet (Hanel et al (1981)). This is a seasonal effect caused by Saturn's 27° obliquity. The radiative time constant at this atmospheric level is approximately equal to the Saturnian year (Cess and Caldwell (1979)), so that the thermal response is expected to lag behind the seasonal forcing by about a quarter of the seasonal cycle, resulting in the observed cold northern hemisphere. On Saturn, the light and dark cloud bands also appear to extend to latitudes of about 70° in each hemisphere.

In figure 1, we have compared the zonal velocities of Jupiter and Saturn, obtained by tracking cloud elements between specific frames of Voyager images. The most noticeable differences between these profiles are the presence of the broad, strong equatorial jets in the atmosphere of Saturn, and the virtual absence of easterly jets. Retrograde jets have been found in the Saturn atmosphere at planetocentric latitudes of $\sim$41, 58,78^{O}N

ZONAL VELOCITY vs LATITUDE on SATURN and JUPITER

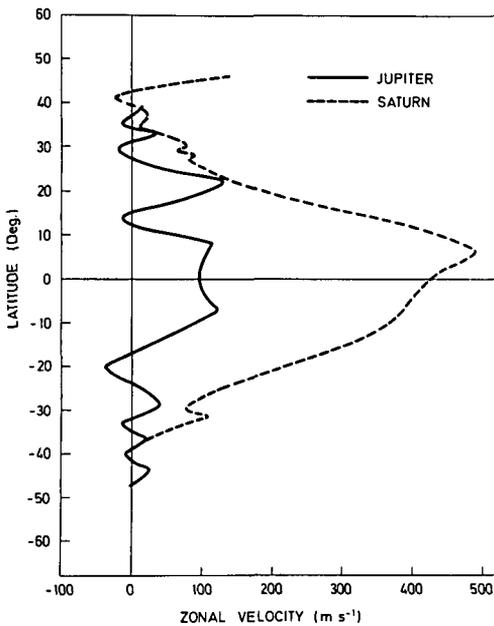
Fig 1 — Comparison of the zonal velocity of
Jupiter (Voyager 1; February 1979)
with that of Saturn (Voyager 1, November 1980).

and 41 and 58°S. These major differences between the zonal wind
profiles must reflect differences in the internal structure and
driving mechanisms of these atmospheres.

Studies of the eddy momentum flux by Beebe et al (1980),
Ingersoll et al (1980) and Hunt (1981) have provided some insight
into possible driving mechanisms which are summarised in figure 2.
Available potential energy for the atmosphere is generated by the
buoyancy of the cloud systems, which is transferred into kinetic
energy by the planetary rotations. However, we find for Jupiter
that the main motions are being driven by the conversion of eddy

EMITTED INFRARED
RADIATION • E

DISSIPATION • D

POTENTIAL
ENERGY • P
(BUOYANCY)

GENERATION • G

KINETIC
ENERGY • K
(WIND)

ZONAL

CONVERSION • C

EDDY

INCOMING SOLAR RADIATION
AND CONVECTED INTERNAL ENERGY • I
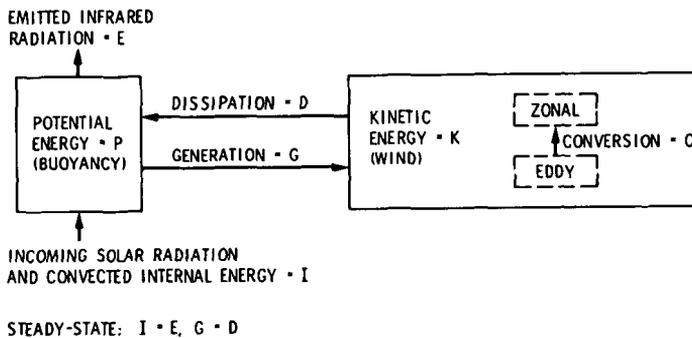
STEADY-STATE: I • E, G • D

Fig 2 - A schematic representation of the energy balance
        mechanisms for the generation of the motions in
planetary atmospheres

kinetic energy into zonal mean kinetic energy as in the Earth's
atmosphere (Holton (1972)). The rate of conversion of eddy kinetic
energy into mean kinetic energy is in the range 1.5 to 3 $W.m^2$ for a
layer 2.5 bars deep. The time constant for resupply of zonal mean
kinetic energy by the eddies is in the range of 2-4 months, which is
less than the interval between the Voyager encounters. Clearly,
this situation cannot proceed unbounded, so that some larger
atmospheric system must therefore owe its existence to the extraction
of eddy momentum from the flow in which it is embedded. It is
possible that the Great Red Spot and the white ovals behave in this
way. The zonal wind profiles shown in figure 1 illustrate

essentially no correlation with the banded structure of either
Jupiter or Saturn (Ingersoll et al (1980), Hunt (1981), Smith et al
(1981)). This suggests that the visible clouds are controlled by the
radiative/dynamical properties within the upper troposphere and
clouds rather than in the deep atmosphere associated with the jets.

The rate of conversion is more than 10% of the total infrared
heat flux for Jupiter in contrast to 0.1% for the Earth. This 100
fold difference suggests that the thermomechanical energy cycles are
very different on the two planets. It is certainly possible that
the zonal flux extends much deeper than the eddies and therefore is
affected on a timescale much longer than four months. The stability
of the Jovian (and Saturnian) jets over time periods of centuries,
which is in complete contrast to the rapidly varying visible
appearance of the planet, is consistent with the assumption that the
jets are associated with the deeper layers of the atmosphere.

To explain the differences in the zonal profiles of the
planets shown in figure 1, we note that for Jupiter internal
heating supplies less energy to the atmosphere than solar heating.
For Saturn, however, internal heating supplies roughly twice the
energy than is received from solar heating. This internal heating
would tend to increase the relative importance of small scale
convection on Saturn. In addition, Saturn has a lower value for
gravity, which leads to a larger atmospheric scale height, and a
corresponding larger scale of convective motions. This would then
tend to increase the amount of available potential energy of the
system, which, on a rapidly rotating planet, would produce the
observed stronger motions (figures 1 and 2). It is apparent there-
fore that the energy cycle for these planets provides the basic
information to explain the observed flows, which should be taken
into account when we now address Uranus and Neptune, where
considerably less observational information is available.

THE METEOROLOGIES OF URANUS AND NEPTUNE
Uranus is the first planet so far from Earth that dynamical
activity, manifested by clouds, cannot be easily observed by ground

based observations. Consequently, we have no direct knowledge about
atmospheric motions. Our knowledge about the structure of the cloud
layers, which would act as a tracer of any motions, is itself very
limited. While methane cloud layers could form in the atmosphere
(Belton (1981)), it is also possible that any structure within this
cloud would be obscured from view by extensive aerosol layers. At
deeper levels, layers of NH_3 cloud and NH_4SH clouds are expected.
The observed changes in the microwave spectrum of Uranus by Klein and
Turegano (1978) are possibly due to variations in the structure of
these deep clouds.

   Both Uranus and Neptune show long term brightness changes in
the visible portion of the spectrum. Lockwood and Thompson (1978)
have found a 1% increase in the absorption in the 6190 and 7261Å
CH_4 bands over a two month interval. Observations from 1953 to 1965
show that the B magnitude of Neptune increased from 0.02 mag., while
that for Uranus decreased from 0.04 mag. Then from 1972 to 1976,
Neptune brightened by 0.007 mag/year, while the brightness of Uranus
changed by 0.012 mag/year. These changes are certainly the result
of variations in the solar UV flux, which then alters the albedo of
the planet through the corresponding photochemical and constituent
changes to the upper atmosphere and clouds. This suggests that the
radiative budget of these planets, which must be important in the
general circulation of these planetary atmospheres, will possess
some significant variations, and thus influence the motions.

   While the images of Jupiter and Saturn show definite detail
of the light/dark cloud structures, there is little to suggest that
Uranus and Neptune have a banded appearance. Alexander (1965)
suggested that when the equatorial regions of the planet are visible
and the viewing excellent two faint belts on either side of a
bright zone are sometimes seen on Uranus, using larger telescopes.
Antoniadi thought that when he observed the planet, the belts
appeared exactly parallel to the general plane of the satellite
orbits and not tilted at about 20° as other observers had reported.
Dollfus (1970) remarked that the features he saw did not seem to be
belts. The best image currently available, taken at 890nm, shows

evidence of the bright limb of Uranus, which is suggestive of a haze
layer high in the atmosphere (see Smith (1981)). Neptune has been
more difficult to observe, and the observations by Smith (1981) show
possible evidence of cloud structure with a dark equatorial belt
separating brighter regions in each hemisphere.

It is necessary to examine the basic atmospheric properties of
the planets, which are summarised in Table 1.

TABLE 1: Basic Properties of Planetary Atmospheres

	Albedo	Effective Temp(^{O}K)	Measured Temp(^{O}K)	Adiabatic Lapse Rate (^{O}K/km)	Radiative Time Constant
Earth	0.30	256	256	∿9.8	∿60 days
Jupiter	0.33±0.02	106	124.9±0.3	1.9	∿6 yrs
Saturn	∿0.36	76±4	96.5±2.5	0.9	∿6 yrs
Uranus	0.34-0.5	55-58	58±2	∿1.0	∿600 yrs
Neptune	0.34-0.5	43-46	∿55	∿1.4	∿2200yrs

These tabulations indicate that, unlike the other major planets,
Uranus does not appear to possess an internal heat source to provide
an additional driving mechanism for the motions. The long radiative
time constant compared with the length of the Uranian day (Houghton,
1977; Goody, 1981) would suggest a relatively more stable atmosphere
than the other planetary atmospheres. Stone (1973, 1975) suggested
that the Richardson number may be as large as 2800, confirming this
interpretation.

Uranus does, however, possess some important differences from
the other planets. The large inclination of the axis of rotation
will mean that each hemisphere will spend a substantial period
without sunlight once each Uranian year. At the present time, the
north pole of the planet is just turning towards the Earth after
having turned away from the sun for more than 40 years. The
atmosphere will then cool substantially in the absence of meridional
heat transport.

Although Uranus has a rapid rotation period of 16.31±0.27 hrs

(Goody (1981)), the large inclination of the equator means that
during the course of one orbit all equatorial regions receive less
heat from the sun than the polar latitudes. Consequently, the poles
will be hotter than the equator, so that from the thermal wind
equation the mean zonal winds will be easterly, in contrast to the
mean westerly winds of Jupiter and Saturn.

Even in the absence of any major internal heating, it is
natural to expect that on a rapidly rotating planet certain
natural horizontal scales of motion will be generated. We may
anticipate barotropic instabilities of $\sim$1000km and baroclinic
instabilities of $\sim$600km for a mean velocity of $\sim$2ms^{-1}. The
corresponding time scales of these features would be about 40 days
and 8 days respectively. We would not necessarily expect to find
large scale convective motions in the atmosphere of Uranus. As a
consequence, we may expect the motions to be far less turbulent
than on Jupiter and Saturn, and possibly even the Earth.

Neptune may, however, have large scale motions. Joyce et al
(1977) have observed a factor of four change in the reflectance
of the planet between 1 and 4µm during the period 1975-76, while the
simultaneous measurements of Uranus showed a negligible change.
More recently, Cruikshank (private communication (1981)) has
reported similar rapid changes in the structure of Neptune. Pilcher
(1977) suggested that these changes could be accounted for by large
scale variations in the cloud structure. Since the observations
refer to the whole planetary disk, we may anticipate considerable
structure in the cloud layers when higher spatial resolution
observations are made later this decade. Certainly, it is possible
that Neptune could have strong motions. Belton et al (1981) believe
that the simultaneous presence of three periodicities of 17.73,
18.56 and 19.29 hours for the rotational period of the planet,
together with related harmonics in the J-K colour, is consistent
with zonal winds of up to 109ms^{-1}. Furthermore, the internal
heating would be dominant over the available absorbed solar energy
and therefore by the energy budgets of figure 2, leading to strong
motions.

CONCLUSIONS

The meteorology of Uranus may be quite different from the motions of the other large planets. The apparent absence of internal heating and the large obliquity of the axis of rotation on this rapidly rotating planet make Uranus quite different from its planetary neighbours. We anticipate only weak motions, generated primarily by the differential solar heating, which, at the time of the Voyager encounter in 1986, will be a maximum in the polar region. The meteorology of Uranus provides a major test of our understanding of planetary weather systems, and must be monitored by Space Telescope during the next decade to extend the high spatial Voyager observations.

REFERENCES

Alexander, A.F.O'D (1962) The Planet Saturn (Faber and Faber)

Alexander, A.F.O'D (1965) The Planet Uranus (Faber and Faber)

Beebe, R.F., Ingersoll, A.P., Hunt, G.E., Mitchell, J.L. and Müller, J-P (1980) Measurements of Wind Vectors, Eddy Momentum Transports and Energy Conversions in Jupiter's Atmosphere from Voyager 1 Images. Geophys. Res. Letts. 7, 1-4

Belton, M.J.S. (1981) An Introductory Review of our Present Understanding of the Structure and Composition of Uranus' Atmosphere (this volume)

Belton, M.J.S., Wallace, L. and Howard, S. (1981) The Periods of Neptune; Evidence for Atmospheric Motions. Icarus (in press)

Cess, R.D. and Caldwell, J. (1979) A Saturnian Stratospheric Seasonal Climate Model. Icarus 38, 349-357

Dollfus, A. (1970) New Optical Measurements of the Diameters of Jupiter, Saturn, Uranus and Neptune. Icarus 12, 101-117

Goody, R. (1981) The Rotation of Uranus (this volume)

Hanel, R. et al (1981) Infrared Observations of the Saturnian System from Voyager 1. Science 212, 192

Holton, J. (1973)   An Introduction to Dynamical Meteorology
     (Academic Press)

Houghton, J. (1977)   The Physics of Atmospheres (CUP)

Hunt, G.E. (1981)   The Atmospheres of Jupiter and Saturn. Phil.
     Trans. Roy. Soc. (in press)

Ingersoll, A.P., Munch, G., Neugebauer,G., Orton, G.S. (1976)
     Results of the Infrared Radiometer Experiment on Pioneers 10
     and 11 in Jupiter (ed.by T. Gehrels) p.197-205. University
     of Arizona Press

Ingersoll, A.P., Beebe, R.F., Mitchell, J.L., Garneau, G., Yagi, G.,
     Müller, J-P and Hunt, G.E. (1980)   Interaction of Eddies and
     Mean Zonal Flow on Jupiter as Inferred from Voyager 1 and 2
     Images. J. Geophys. Res. (in press)

Joyce, R.R., Pilcher, C.B., Cruikshank, D.P, and Morrison, D. (1977)
     Evidence for Weather on Neptune I. Astrophys. J. 214, 657-
     662

Klein, M.J. and Turegano, J.A. (1978)   Evidence of an Increase in
     the Microwave Brightness Temperatures of Uranus. Astrophys.
     J. 224, L31-34

Kondratyev, K.Ya and Hunt, G.E. (1981)   Weather and Climate on
     Planets (Pergamon Press)

Lockwood, G.W. and Thompson, D.T. (1978)   A Photometric Test of
     Rotational Periods for Uranus and Time Variations of Methane
     Band Strengths. Astrophys. J. 221, 689-693

MacFarlane, J.J. and Hubbard, W. (1981)   Internal Structure of
     Uranus (this volume)

Peek, B. (1958)   The Planet Jupiter (Faber and Faber)

Pilcher, C.B. (1977) Evidence for Weather on Jupiter II.
     Astrophys. J. 214, 663-666

Smith, B.A. et al (1979a)   The Jupiter System through the Eyes of
     Voyager 1. Science 204, 951-972

Smith, B.A. et al (1979b) The Galilean Satellites and Jupiter :
     Voyager 2 Imaging Science Results. Science 206, 927-951

Smith, B.A. et al (1981)   Encounter with Saturn:Voyager 1 Imaging
     Science Results. Science 212, 163-191

Smith, B.A. (1981)   Imaging Studies of the Outer Planets (this
     volume)

Smith, B.A. and Hunt, G.E. (1976) Motions and Morphology of Clouds
        in the Atmosphere of Jupiter   in Jupiter (ed.by T. Gehrels)
        (University of Arizona Press)

Stone, P. (1973) The Dynamics of the Atmospheres of the Major
        Planets. Space Sci. Rev. 14, 444-459

Stone, P. (1975) The Atmosphere of Uranus. Icarus 24, 292-298