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AUTUMN COLLEGE
ON
THE TROPOSPHERE, STRATOSPHERE AND MESOSPHERE
10 September - 19 October 1984

THE GIANT PLANETS: GALILEO GALILEI TO PROJECT GALILEO

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Presidential address to the Royal Astronomical Society, delivered 10 February 1984.

To appear in Quarterly Journal of the Royal Astronomical Society

(Legends for diagrams are on pp 36-40)

1. INTRODUCTION

A famous American politician admitted that he knew only two songs, "one was Yankee Doodle Dandee and the other one was'nt". In recent years, as friends have reminded me, I have fallen into the habit of responding to invitations to give general talks by offering a choice between two possible topics. So far as the Royal Astronomical Society is concerned, I used one of them up, so to speak, when I delivered the 1981 Harold Jeffreys lecture on "Rotating fluids in geophysics and planetary physics". So "Giant planets" it has to be. But I make no apology for this choice of topic as a presidential address to this Society of astronomers and geophysicists, including planetary scientists, which rejoices in a long tradition of fostering cooperation and mutual respect between workers from the wide range of disciplines involved in the study of the cosmos.

Planetary science, once at the very centre of astronomy, is now very properly regarded as an extension of basic geophysics, and can be defined in its widest sense as including all aspects of the scientific study of processes occurring in the main bodies and the gaseous and plasma envelopes of all the planets and other objects in the solar system. The study of planets (other than Earth) as physical objects and not just moving points of light goes back to the early seventeenth century, when Galileo Galilei discovered Jupiter's four main satellites and initiated the observations that led to the discovery of Saturn's rings by Christian Huyghens. But systematic work in planetary science is a comparatively recent development which has accompanied the rise of modern geophysics and astrophysics. Planetary research is based on a variety of observations. Many are made with

ground-based instruments at wavelengths in the electromagnetic spectrum where the Earth's atmosphere is transparent or only weakly absorbing, namely the visible range from 0.4 to 0.8 microns, various "windows" in the infrared, and the radio spectrum from about 1 millimetre to the ionospheric cutoff at about 100 metres. Other important observations come from instruments carried on rockets, aircraft and balloons, operating at levels where effects due to ozone, which absorbs ultraviolet radiation, and water vapour, which absorbs in the infrared, are much weaker than at ground level.

The most recent data include abundant measurements made with instruments mounted on space probes, which, in the case of the giant planets Jupiter and Saturn, were the Pioneer 10 fly-by, which encountered Jupiter in 1973 December before heading out of the Solar System, Pioneer 11, which encountered Jupiter in 1974 December and Saturn in 1979 September, Voyager 1, which encountered Jupiter in 1979 March and Saturn in 1980 November, and Voyager 2, which encountered Jupiter in 1979 July, Saturn in 1981 August and should reach Uranus in 1986 January, eight years after being launched from Earth. At the present time, preparations are well advanced for the next United States planetary mission, Project Galileo, which will be launched by the Shuttle/Centaur about two years hence, in the late spring of 1986, with the objective of carrying out a far more intensive and comprehensive study of the Jovian system than was possible with Voyager. The Galileo spacecraft consists of a sophisticated "dual spin" planetary orbiter, which, starting in August 1988, will provide the first long-term close observations of the Jovian system, including the Galilean satellites, together with an entry probe, which will

provide the first *in situ* measurements of Jupiter's atmosphere. It is a measure of the confidence with which the "Galileo/Jupiter" project is now viewed that considerations are now being given to the possibility of a Galileo-type mission to the Saturnian system, but no details have yet been released.

This article* outlines some of the main characteristics of the giant planets and discusses aspects of their study in which I have been interested for a number of years, namely the circulation of their atmospheres, the structure of their interiors, and the origin of their magnetic fields. Progress with the physical interpretation of the

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*Parts of the article presented here are based on written versions of the 1980 Halley lecture at Oxford University and the 1982 Holweck Prize Lecture at the École Polytechnique in Paris, but brought up to date by the inclusion of recent material. The talk was illustrated with slides and several short films describing, amongst other things, motions of Jupiter's visible surface of dense cloud and laboratory experiments on stable vortices in thermally driven rotating fluids which, in the author's opinion, are dynamically similar to long-lived eddies in the atmospheres of Jupiter and Saturn, including the Great Red Spot. It is impossible to reproduce most of this visual material here and inappropriate therefore to present a verbatim account of the lecture, or even give a full list of references to work mentioned during the lecture. These references can be found in the bibliographies of the selected list of review papers, etc. given at the end of this article.

observational data involves the application of a wide range of available knowledge in physics and chemistry. It also requires the development of new ideas and insights, some of which are only now beginning to emerge, following the comparative neglect suffered by many areas of classical physics during the first half of the present century. As we shall see later, the findings of laboratory studies of hydrodynamical flows in rapidly rotating fluids can play an important direct role in the study of large-scale atmospheric motions, but this is unusual in planetary science and astronomy, where basic processes can rarely be simulated on the scale of the terrestrial laboratory. In the study of the origin of planetary magnetic fields, for example, the theoretician has to work directly with the observations and the basic laws of physics.

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2. JUPITER'S MAIN CHARACTERISTICS

Jupiter is the fifth planet in order of distance from the Sun, which it orbits in 11.9 years at a mean distance of 5.20 astronomical units. The largest and most massive of the nine planets, Jupiter has a mean radius of 6.97×10^7 metres, more than ten times the radius of Earth, but its mean density is only about one quarter of that of the 'terrestrial' planets, indicating that its main chemical constituent is hydrogen - the lightest and most abundant of all the elements - with helium as the main "impurity". The rapid spin of the planet on its axis, in a period of just under 10 hours, produces a noticeable oblateness in the appearance of the visible disk in a telescope, and the concomitant distortion of the gravitational field of the planet perturbs the orbits of the innermost satellites. These rotational effects are nevertheless somewhat weaker than those expected from a gravitating body of uniform density, implying that the density of Jupiter increases with depth to a central value of about three times the mean density. At 30×10^{11} Pa, Jupiter's central pressure is eight times that of the Earth and sufficient to ensure that throughout most of the planet the main constituent hydrogen takes the metallic form, to which ordinary molecular hydrogen changes when subject to pressures in excess of about 2×10^{11}Pa.

Jupiter is enveloped in several layers of cloud suspended in a deep and well-stirred atmosphere of hydrogen, helium, methane, ammonia and other gases. At some wavelengths it is possible to see below the upper layer of white ammonia cirrus, through a clear region to a more substantial and colourful cloud deck which might consist mainly of particles of ammonium hydrosuphide (NH_4SH). Jupiter's striking and

variable colours are probably due to the presence of products of the photolysis of NH_3, H_2S, PH_3 and other compounds by solar ultraviolet light. Jupiter's clouds reflect back into space most of sunlight incident upon them, the remainder being absorbed at various levels in the atmosphere. Absorbed sunlight accounts for about one-half of Jupiter's thermal (infrared) emission, the balance being due to internal heat sources associated with primordial heat and slow gravitational contraction of the planet. The outward heat flow should maintain the temperature gradient close to its adiabatic value throughout most of the planet.

From their studies of Jupiter's strong emission of non-thermal radiation at decimetre and decametre wavelengths, radio-astronomers established that Jupiter possesses a strong dipole magnetic field inclined at about 10 degree to the rotation axis, and an associated system of van-Allen-type 'radiation' belts of electrically-charged particles with relativistic energies, extending beyond and interacting with the innermost Galilean satellite Io. The decametric radiation, which comes in bursts and is modulated by Io, is still not fully explained. More detailed information on the structure of Jupiter's magnetic field and magnetosphere and their interactions with the solar wind came later from in situ measurements made with instruments on the Pioneer and Voyager fly-by space probes.

Jupiter's non-uniform rotation is reflected in the early use by optical astronomers of two longitude systems when studying spots and other markings on the planet's visible disk. These were System I with rotation period 9 hours 50 minutes 30.003 seconds for features within about 7t of the equator; and System II with rotation period 9 hours 55

minutes 40.632 seconds for higher-latitude features. System III -with period 9 hours 55 minutes 29.710 seconds (formerly 29.390 seconds) -was subsequently introduced for the convenience of radio astronomers studying Jovian decametric and decimetric sources. These are nearly fixed in System III and presumably tied to Jupiter's magnetic field which, in turn, is intimately linked to the electrically-conducting part of the interior of the planet, but not with the overlying non-conducting layers, including the atmosphere. The interpretation of Jupiter's non-uniform rotation presents a variety of fascinating scientific problems involving the consideration of the dynamics and magnetohydrodynamics of Jupiter's atmosphere and deep interior, just as the theoretical interpretation of the general eastward motion (on average) of the terrestrial atmosphere relative to the solid Earth, the general westward motion of the geomagnetic field relative to the solid Earth, and fluctuations in the rotation of the solid Earth, involves the discussion of fluid motions in the Earth's atmosphere, oceans and liquid core.

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3. JUPITER'S ATMOSPHERIC MOTIONS

Prominent markings on Jupiter's visible surface are the bright cloud zones - of which there are usually about seven or eight - which run parallel to the equator and are separated by darker belts. The zones and belts are not entirely regular: dark patches often appear on the brighter regions and bright patches on the darker regions, and the boundaries between belts and zones often taken on a serrated shape. The most striking feature of all is the long-lived Great Red Spot (see figure 1) which is certainly 150 years old at least and may have been seen by Hooke and Cassini in the seventeenth century. The Great Red Spot is roughly elliptical in shape, having its long axis along 'zenocentric' latitude 22t South, and occupies about 30t of longitude and 10t of latitude.

FIG.1 near here

The movement of irregular markings seen on the visible disk yields information about the rotation of the planet at the upper cloud level as a function of latitude. As we have already noted, rotation periods of markings within about 7t of the equator are typically about 5 minutes less than typical rotation periods of most higher-latitude features (and of radio sources), showing the presence of a sharply-bounded westerly equatorial jet-stream moving at about 100 ms^{-1} relative to the underlying planet. During the past 100 years the period of rotation of the Great Red Spot has varied irregularly by about 3 seconds (or 360 parts in a million). Superimposed on this irregular variation is a comparatively tiny but evidently persistent oscillation with a period of about 90 days. But (in comparison with the Earth's atmosphere for example) the overall latitudinal variation of rotation period shows remarkably little time dependence.

Motions occur in planetary atmospheres because the special conditions for stable or neutral hydrostatic equilibrium cannot in general be met when heat sources are present. These conditions for a fluid of low viscosity in a steady gravitational field are that the density field should have no horizontal gradients, and that vertical density gradients should nowhere exceed the adiabatic value. Owing to the general intractability of the equations of hydrodynamics and uncertainties in several important parameters (such as the atmospheric depth), theoretical work on the circulation of Jupiter's atmosphere has been largely confined to the construction of simple models of the main phenomena indicated by the observations, notably the general arrangement of clouds in bands parallel to the equator, the equatorial jet stream and the Great Red Spot and other persistent oval markings. There is no generally accepted explanation of any of these phenomena, but their study has stimulated important investigations in basic hydrodynamics, thereby advancing an important branch of classical physics. Recent theoretical work includes studies based on numerical models and the application of modern ideas about solitons and two-dimensional turbulence.

The very existence and durability of the Great Red Spot present a strong challenge to theoreticians, particularly those dynamical meteorologists and geophysical fluid dynamicists who are concerned with the important practical question of atmospheric predictability. Several incomplete suggestions have been made as to the origin of the Great Red Spot and other long-lived eddies in Jupiter's atmosphere, such as the three White Ovals that were seen to form in 1939 and are clearly visible in the recent Voyager pictures. I argued in my Halley

lecture several years ago that these long-lived eddies might be dynamically similar to the closed stable baroclinic eddies found in the regular non-axisymmetric flow regime investigated in experiments on thermal convection in a rotating fluid annulus subject to horizontal temperature gradients produced by internal heating and side-wall cooling, where they are largely responsible for horizontal and vertical heat transfer. In some new laboratory and numerical studies of the structure, energetics and stability of such eddies (further details of which are given in the Appendix), Dr Peter Read and I find results confirming that there are strong dynamical similarities between these atmospheric and laboratory flows (see figures 2 and 3) and that the basic dynamical processes involved might also account for the dark long-lived cyclonic features known as "barges". In particular, the horizontal upper level motion in each anticyclonic eddy is largely confined to a peripheral jet stream, where there is strong shear, enclosing a comparatively quiescent region in which slow upwelling occurs. Surrounding the peripheral jet stream is a narrow region of downwelling, a feature which could account for the "collar" of enhanced infrared emission surrounding the Great Red Spot. Upper level cyclonic features would have oppositely-directed vertical motions.

FIGS. 2 & 3 new here

In this baroclinic eddy hypothesis, the energy required to produce and maintain the kinetic energy of the eddy against the dissipative action of viscosity derives largely from the potential energy due to gravity acting upon the density field associated with local horizontal temperature gradients. Coriolis forces due to the rotation of the planet play a crucial role in the hypothesis, but the

so-called "beta-effect" associated with the latitudinal variation of the vertical component of the rotation of the planet produces no direct influence. The beta-effect is also unimportant in the hypothesis that long-lived Jovian atmospheric eddies are analogous to terrestrial hurricanes, where the release of latent heat of condensation, in motions involving small-scale moist convection organized by Coriolis forces and friction, provides the energy source. It is in the so-called "soliton" and "modon" theories where the beta-effect plays a crucial direct role. These theories differ from one another in the assumption made as to the source of energy required to overcome viscous dissipation, with the "soliton" drawing its energy directly from the kinetic energy of the background zonal shear flow, and the "modon" being produced by the coalescence of smaller eddies.

Attempts are now being made to formulate for the forthcoming Galileo mission a practical programme of crucial observations that would settle some of these dynamical issues, but it is by no means clear how effectively this can be done. No-one can dispute that atmospheric motions are largely quasi-geostrophic, for simple order of magnitude arguments suffice to demonstrate that this must be so, and associated with geostrophic balance between horizontal pressure gradients and Coriolis acceleration is the thermal wind relationship between horizontal temperature gradients and vertical gradients of the horizontal wind. But it is notoriously difficult to measure these dynamically important horizontal temperature and pressure gradients, and to be useful determinations of vertical temperature gradients must be sufficiently accurate to reveal departures from the adiabatic value. Indeed, it can be argued that the main task of the Jovian

[redacted]logist should perhaps be to use observations of dynamical features that manifest themselves at the upper cloud level and of other observations such as spatial variations of infra-red emission in order to improve our knowledge of the vertical structure of the planets. Many controversial issues are being debated by those of us who take an interest in these matters, including the depth to which upper-level dynamical features penetrate, estimates of which range from less than one hundred to over ten thousand kilometres. A related question concerns the depth at which the electrical conductivity of the planet becomes sufficiently large for magnetohydrodynamic effects to occur, upsetting geostrophic balance and producing, through the self-exciting homogeneous dynamo process, the electric currents that manifest themselves as the observable magnetic field outside the planet.

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4. JUPITER'S MAGNETISM AND INTERIOR

The existence of a strong Jovian magnetic field of internal origin and nearly dipolar form, with a dipole moment about 10^4 times the magnitude and opposite in sign to that of the Earth's present field, was, as we have already noted, first inferred from radio-astronomical observations of non-thermal radiation at decimetre wavelengths, produced by magnetically-trapped relativistic electrons. Such an electron typically spends most of its time near the mirror points of its orbit, moving in a flat spiral around a magnetic field line, and this accounts for the signficant degree (about 25 per cent) of linear polarization of the total decimetre emission. The direction of polarization, which is roughly parallel to Jupiter's equator and fluctuates with the System III rotation period, indicates that the dipole axis is inclined at about 10 degrees to the rotation axis. The observed time variations of the direction of polarization differ slightly from those expected from a purely dipole field, showing that Jupiter's magnetic field possesses a weak non-dipolar component. The decimetre radiation also shows some degree of circular polarization, as would be expected if some of the radiation emerges in directions parallel to lines of magnetic force. Indeed, it was from the observed sense of polarization that it was first concluded that Jupiter's dipole moment is roughly parallel to the rotation axis (unlike the present alignment of the Earth's magnetic dipole, which is roughly anti-parallel to the rotation axis). Such a polarity is evidently consistent with the sense of elliptical polarization of decametre bursts, which is almost invariably right-handed.

Direct measurements of the Jovian magnetic field generally confirm inferences drawn from radioastronomical observations and add many important details. Instruments on board the Pioneer 10 and Pioneer 11 spacecraft provided the first such measurements of the field structure and charged-particle density in the Jovian magnetosphere. The magnetosphere is closed and blunt in shape, with a well-defined magnetopause. Its outer regions are strongly influenced by the fluctuating pressure of the solar wind, which produces changes of up to a factor of two in the size of the dayside magnetosphere. A prominent feature of the mid-magnetosphere is a thin annular current sheet which co-rotates with the planet like a rigid body. The sheet lies almost parallel to the Jovian equator, but is distorted, so that it lies above the equatorial plane on one side of the planet and below on the other. Voyager 1 and Voyager 2 provided further information about the highly complex behaviour of Jupiter's magnetosphere.

Theories of the observed modulation of Jovian decametre bursts by the innermost Galilean satellite Io suppose that Io's motion through the Jovian magnetic field induces electric currents of about 5×10^6 amps in the plasma occupying the magnetic flux tube connecting Io to Jupiter's ionosphere. Direct evidence for this current was obtained during the Voyager mission. The passage of the current through the surface layers of Io would produce 10^{12} watts of ohmic heating there. The extent to which this heating contributes to the processes responsible for violent eruptions of material from Io's surface is not yet settled, for it is somewhat less intense than heating due to gravitational tides (the estimation of which led to the prediction

that eruptions should occur, which appeared in a paper published just before Voyager TV pictures provided spectacular confirmatory evidence!).

The only serious suggestion as to the origin of Jupiter's magnetic field closely parallels ideas developed by geophysicists over the past thirty years towards an explanation of the Earth's magnetism. The Jovian magnetic field is due to ordinary electric currents circulating in conducting regions within the planet. The currents are produced by the self-exciting magnetohydrodynamic (MHD) dynamo process - first suggested by Larmor - involving inductive interactions between fluid motions and the magnetic field. Whether dynamo action is possible depends <u>inter alia</u> on the value of the so-called 'magnetic Reynolds number' $\sigma\mu LU$, where σ is the electrical conductivity, μ the magnetic permeability, L a typical length scale, and U a typical speed of relative fluid motion. Such action cannot occur when $\sigma\mu LU$ is very small, for then motional induction cannot overcome effects of ohmic dissipation. It is also impossible or inefficient when $\sigma\mu LU$ is very large indeed, because dynamo action involves not only the amplification of magnetic energy but also the diffusion of field lines from the conducting region into the surrounding insulator, which is impossible when the conductor is perfect. Efficient dynamo action should occur in those parts of the planet where $\sigma\mu LU$ has some optimum value R , which might be around 10 or 100.

The broad features of the internal structure of Jupiter have now been elucidated. Theoretical models are sensitive to the assumed equations of state of the main constituents, hydrogen and helium. Recent work indicates that the planet is probably fluid throughout,

with outward heat flow taking place largely by convection. At some future stage of the evolution of the planet, the settling of helium "raindrops" in the metallic core should convert gravitational into thermal energy at a substantial rate.

Dynamo action would occur in those regions well below the visible surface of the planet, radius r_s , where the electrical conductivity σ is about equal to $R/\mu LU$. Denote by r_c the outer radius of the electrically-conducting region in which dynamo action is occurring and by r_m the mean radius of the boundary where the pressure attains the value (about 2 x 10^{11} Pa) at which molecular hydrogen changes to the metallic form. Estimates of r_m range from 0.7 r_s to 0.8 r_s, and it is possible but not certain that r_c is equal to r_m . Impurities and high temperature and pressure might render the molecular hydrogen 'mantle' sufficiently conducting in its lower reaches to support dynamo action there and, if this is so, r_c could be significantly greater than .

I have introduced a method for finding r_c which exploits the fact that over short intervals of time the magnetic flux linkage of the surface of the core cannot change significantly (see figure 4). This method makes use of observations of secular changes in the magnetic field in the accessible region above the surface of the planet. When applied to the Earth using the best available determinations of the geomagnetic secular variation, the method gives r_c to within 2% of the more accurate "seismological" value, but even the best Jovian magnetic field determinations currently available for this purpose are not good enough to give a reliable value of r_c for Jupiter. The rough determinations that have been made could be

FIG.4 near here

greatly improved on in the future if detailed magnetic measurements can be carried out with the aid of the Jupiter orbiter on the forthcoming "Galileo" mission. The determination of r_c will be important in the study of the dynamics as well as the structure of Jupiter's interior. The rotation period of System III is close to that of material at a depth $r_s - r_c$ below the visible surface of the planet. The best we can say at present is that this depth is probably around 20,000 km but it might be as small as 7000 km, one tenth of the mean radius of the planet.

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5. SATURN

Saturn is the sixth planet in order of distance from the Sun, which it orbits in 29.5 years at a mean distance of 9.55 astronomical units. The outermost of the planets known in remote antiquity (before the discovery of Uranus, Neptune and Pluto from telescopic observations), Saturn is second only to Jupiter in size (mean radius 5.74 x 10^7 metres) and mass and has the low mean density expected of a planet composed mainly of hydrogen and helium. Saturn possesses a rich satellite system, which includes Titan, the only satellite in the solar system showing evidence of an atmosphere. It also includes the beautiful rings of Saturn, which comprise an enormous number of discrete rocky fragments which may have been produced by the tidal disruption of a larger object (see figure 5).

Fig.5 new here

Saturn is comparable with Jupiter as a reflector of sunlight and, like Jupiter, is also enveloped in dense clouds of ammonia crystals suspended in an atmosphere of hydrogen, helium, methane and other gases and arranged in bands parallel to the equator. These bands appear to be more regular than those on Jupiter, irregular markings being comparatively rare in ground-based observations. Colour variations on Saturn are much less pronounced than on Jupiter and nothing quite comparable with Jupiter's Great Red Spot has ever been seen on Saturn, but Voyager TV pictures of Saturn show a variety of interesting atmospheric disturbances, which are now providing a basis for dynamical studies. As with Jupiter, in order to account for Saturn's infrared emission it is necessary to invoke a substantial source of internal heating.

Transits of long-lived spots on Saturn (including one investigated in the early 1930's by the well-known English comedian Will Hay) yield rotation periods of 10 hours 13 minutes within about 20° of the equator and 10 hours 40 minutes at higher latitudes. Voyager observations provided important new details, confirming the presence at the upper cloud leve of Saturn's atmosphere of an equatorial current moving eastward at more than 400 metres per second, four times the speed of Jupiter's equatorial current. Hydrodynamical theory indicates that the width of an equatorial current should be roughly proportional to the square root of its speed, and this accords with the observations.

Saturn's equatorial diameter exceeds its polar diameter by more than 10 per cent, the corresponding degree of oblateness being bigger than Jupiter's but, again, rather less than that of a rotating gravitating body of uniform density. Saturn does not differ greatly from the Earth in its surface gravity and central pressure. On recent ideas concerning its internal structure, in contrast with the planet Jupiter the internal temperatures of Saturn are probably no longer sufficiently high for helium to dissolve at any level within metallic fluid hydrogen core, implying that gravitational settling of helium might be playing a significant role in the production of heat within the planet at the present time.

The first evidence that Saturn possesses a general magnetic field came nearly a decade ago with the detection of weak non-thermal radio emission at hectametre wavelengths. Pioneer 11 encountered Saturn in 1979 September and its magnetometers showed that the planet has a dipole moment inclined by less than 2° to the rotation axis with a strength about 0.1 times that of Jupiter. General dynamical

considerations indicate that the rotation rate of Saturn's interior should be much closer to that of the atmosphere in middle and high latitudes (10 hours 40 minutes) than to that of atmospheric markings near the equator (10 hours 13 minutes). This expectation was confirmed by determinations of the rotation period of Saturn's hectametre radio sources, 10 hours 40 minutes.

Saturn's magnetic field is attributable, presumably, to a magnetohydrodynamic dynamo driven by fluid motions in the deep interior. A basic tenet of dynamo theory (which has recently been proved quite rigorously) is that no steady or unsteady magnetic field that everywhere retains an axis of symmetry can be supported by dynamo action. But some theoreticians have been misled into questioning this result on the basis of the near coincidence of Saturn's magnetic and rotation axes and the very strong predominance of the dipole component in the observed field. These features of the field are more readily explained in terms of the comparative smallness and other properties of Saturn's electrically-conducting fluid core.

Information about Saturn, though still much less abundant than for Jupiter, now includes new data from recent Pioneer and Voyager encounters, which are transforming all aspects of the study of Saturn's interior, magnetic field, atmosphere, magnetosphere and satellites. Particularly noteworthy is the resurgence of interest in the dynamics of the rings following the acquisition of high resolution pictures showing fine detail and other features of their structure.

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6. CONCLUDING REMARKS

I end the main part of this article on a personal note, by mentioning that (in common with many other scientists) I had my interest in planets stimulated by the late Professor Harold Urey. The circumstances were, however, a little unusual. In 1954 Professor S. Chandrasekhar, with whom I was working at the time, kindly took me to lunch at the Quadrangle Club at the University of Chicago. Urey was in the party, and on my being introduced to him as a member of the Yerkes Observatory, he characteristically fired a very direct question at me: "What do you think about the Red Spot on Jupiter?" Until that moment I was not even aware of having heard about the Great Red Spot, let alone given thought to the problem of its origin, but divine intervention, manifested as a spilt tumbler of water, spared me the embarrassment of having to respond to Urey's question. As we settled down to our meal after the waitress had cleared up the mess, Urey re-directed the conversation to a topic which was much on his mind at that time (and one with which I happened to be reasonably familiar), namely Rayleigh-Taylor instability and the possibility of its occurrence in the mantle of the Earth.

But his question about the Red Spot must have sunk into my deep subconscious, to emerge several years later, in 1959, when I produced what subsequently became known as the Taylor-column theory of the phenomenon, which earned me considerable notoriety amongst my fluid dynamicist friends. Planetary scientists were thin on the ground twenty-five years ago, but I received some encouragement from several of their number, most of whom were dedicated amateur astronomers. They included the late Mr B. M. Peek, a well-known member of this Society

and professionally a schoolmaster, who deserves much credit not only for his observations of Jupiter and his timely book on the subject published in 1958 (and also for setting some of his ablest pupils, including certain members of this Society, on careers that were to bring them great distinction in astronomy and other branches of science). Until the late 1960's, I was able to work at my job as a fluid dynamicist and still keep up with developments in planetary sciences by reading the literature, attending the occasional meeting, and corresponding with other enthusiasts. But this is no longer possible owing to the burgeoning of planetary sciences in the past decade, and experts well aware of the superficiality of many parts of this general talk will doubtless urge me to consider making it the last one I dare present on the subject of the giant planets!

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APPENDIX: LONG LIVED EDDIES IN THE LABORATORY AND IN THE ATMOSPHERES OF JUPITER AND SATURN

My laboratory at the Meteorological Office has been engaged for a number of years in experiments with rotating fluids, including numerical modelling, and in various studies of the dynamics of large-scale motions in the atmospheres of the Earth and other planets, all with the general aim so far as terrestrial meteorology is concerned of providing a sound basis for theories of predictability. The meandering jet-streams of the mid-latitude circulation of the Earth's atmosphere exemplify many of the salient characteristics of flows in rapidly-rotating fluids, and so do the large oval eddies in the atmospheres of Jupiter and Saturn, including the Great Red Spot. But detailed and subtle considerations are required in order to understand why, on the one hand, the large oval eddies on Jupiter and Saturn enjoy lifetimes ranging from decades to centuries, whereas, on the other hand, large-scale motions in the Earth's atmosphere are highly chaotic. Laboratory studies of thermal convection in a rotating fluid annulus have thrown considerable light on these questions, and in some very recent work, Dr Peter Read and I have demonstrated that the process of "slantwise" or "sloping" convection (which is now invoked not only in the study of planetary atmospheres but also in the study of the dynamics of stars and even of galactic accreting disks!) can account for many of the observed properties of the long-lived eddies in the atmospheres of the giant planets. This implies that the eddies are involved in the horizontal transport of heat towards or away from the edges of the atmospheric zones or belts in which they

occur, and that their kinetic energy derives directly from the action of gravity on the density field associated with horizontal gradients of temperature.

In a paper due out in Nature later this month (where detailed references can be found) Dr Read and I describe our most recent findings. These bear on the interpretation of the isolated nature of the Great Red Spot, and they include the crucial demonstration that a single intense stable baroclinic disturbance that is strongly localised in azimuth can form readily when the impressed conditions are close to the transition from axisymmetric to non-axisymmetric flow.

Our experiments form part of a much wider study of thermal convection in a rotating fluid annulus. The working fluid of mean density ρ_0 occupies an annular container with two vertical, coaxial, thermally conducting cylindrical sidewalls, and thermally insulating endwalls. The whole apparatus is rotated steadily about its vertical axis of symmetry. The character of the flow obtained in the rotating annulus depends on the external conditions, which can be specified in terms of several dimensionless parameters involving the axial and transverse dimensions of the apparatus, d and $b-a$ respectively, the rotation rate Ω, acceleration due to gravity g (which is typically very much greater than $b\Omega^2$), the maximum density contrast $\Delta\rho$ associated with the axisymmetric impressed temperature field, and the kinematic viscosity ν and other physical properties of the working fluid. The most important of these parameters are:

$$\Theta = gd\Delta\rho/\rho_0\Omega^2(b-a)^2 \text{ and } \mathcal{T} \equiv 4\Omega^2(b-a)^5/\nu^2 d. \qquad \text{(1 and 2)}$$

The flow itself strongly modifies the horizontal density field associated with the impressed differential heating and cooling, thereby reducing the horizontal density gradients in the main body of the fluid, away from sidewall and endwall boundary layers. It also produces vertical density gradients which are typically strongly dependent on the upward vertical co-ordinate z but comparatively weakly dependent on the horizontal co-ordinates (r, ϕ). Associated with these vertical gradients can be defined a local 'Brunt-Vaisala' frequency

$$N \equiv \left[-g\rho_0^{-1}\partial\rho/\partial z\right]^{1/2}, \qquad (3)$$

the average value of which is typically $\sim (0{\cdot}8\, g\Delta\rho/\rho_0 d)^{1/2}$. When $\mathcal{T}$ is very much greater than 2×10^5, the character of the flow is found to depend mainly on Θ. At values of Θ exceeding a certain critical value Θ_R of order unity (whose exact value depends on details of mechanical and thermal boundary conditions and with which there is an associated critical average value of N), the flow is axisymmetric, i.e. its properties are independent of the azimuthal co-ordinate ϕ. Regular non-axisymmetric flows (i.e. spatially periodic with dominant azimuthal wavenumber $m \neq 0$ and either steady or temporally periodic) occur within the range $\Theta_R > \Theta > \Theta_I$ where Θ_I is a further critical value of Θ. When $\Theta \lesssim \Theta_I$,

irregular, aperiodic non-axisymmetric flows occur, owing to the onset of barotropic instability associated with the comparatively small azimuthal scale (proportional to m^{-1}) of the baroclinic waves. Both regular and irregular non-axisymmetric flows exhibit fully-developed 'baroclinic' disturbances, in which the kinetic energy of the flow is generated and maintained against viscous dissipation by 'slantwise' convection from the potential energy associated with the density field resulting from the impressed heating and cooling.

The detailed form of the flow pattern in the regular non-axisymmetric regime depends inter alia on the variation with distance r from the axis of symmetry of the impressed temperature field. When heat is introduced (or extracted) internally and extracted (or introduced) via both sidewalls, the r variation of impressed temperature shows a maximum (or minimum) near mid-radius. The corresponding upper level flow pattern largely consists of identical closed, compact, equally-spaced oval eddies. Near the edge of each eddy, the relative flow is concentrated into a 'peripheral jet-stream' circulating in the same sense as the shear of the background azimuthal flow, which is anticyclonic (cyclonic) near the upper surface when the system is subject to internal heating (cooling) and cooling (heating) at both sidewalls.

When Θ is only slightly less than Θ_{R} and J is comparatively large (in excess of 10^7), the upper level non-axisymmetric flow in a typical laboratory experiment near $\Theta = \Theta_R$ is dominated by a steady isolated pair of baroclinic eddies. In Fig 6, panel (a) shows a streak photograph of the flow, and (b) and (c) are derived from the velocity field, obtained using velocities measured from streak images similar to Fig 6(a). The 'eddy' stream function shown in Fig 6(c) is approximately equivalent to the eddy pressure field, assuming the flow to be geostrophic, and was obtained by integrating the above-mentioned velocity field and subtracting the azimuthal mean component. Fig 6(b) shows the flow pattern at this upper level, where the shear of the background flow is anticyclonic. The flow is clearly dominated by a single large anticyclonic eddy accompanied by a weaker cyclonic feature, together spanning no more than about 100° in azimuth. Elsewhere the flow is virtually independent of ϕ. The strength of the cyclonic feature in the flow varies with height, dominating the flow at low levels where the shear of the background flow is also cyclonic. As the transitional value Θ_R was approached more closely than the flow in Fig 6, the upper level cyclonic feature was observed to decrease in strength until it manifested itself as no more than a slight cyclonic curvature of the streamlines near the much more prominent anticyclonic eddy. The eddy stream function in Fig 6(c) emphasises the localised nature of the disturbance, which appears as a strongly modulated pulse of waves with a wavelength of about 120° in azimuth. Once established, the pattern is quite steady, apart from a slow steady azimuthal drift relative to the walls of the apparatus at a rate which depends on a variety of factors (e.g. endwall slope). An m = 2 flow pattern, symmetric about a diameter, was found to occur under the same external conditions as those prevailing for an isolated single eddy (m=1) similar to Fig 6. This is in keeping with previous findings that such

FIG.6 near here

systems are 'intransitive' in the sense that m is not uniquely determined by Θ, J and the other dimensionless parameters in terms of which the impressed conditions of the experiment are specified.

These, together with related results based on a numerical model of the system, demonstrate convincingly that fully-developed 'slantwise convection' can account for many of the observed properties of the long-lived Jovian and Saturnian eddies. Accordingly, the sense of circulation and oval form of the atmospheric eddies result from the non-monotonic latitudinal variation of the background thermal field, the associated zonal flow having strong horizontal (as well as vertical) shear. The compact nature of the eddies, their peripheral jet-streams and associated distribution of vertical motion, and their longevity, are characteristic properties of baroclinic eddies over the wide range of parameter space occupied by the regular non-axisymmetric regime. The isolated nature of the most striking of all the atmospheric eddies, the Jovian Great Red Spot, is evidently characteristic of the regular non-axisymmetric flow close to the transition to axisymmetric flow. The latitudinal scale of the eddies is governed by the spacing of the atmospheric bands of wind and cloud, which we presume here to be produced by other, as yet not fully understood, processes. The variation with latitude of the number of the oval eddies and their longitudinal scale, especially evident on Jupiter (see Fig 7), most probably reflects variations in the width of the atmospheric bands and in the effective local value of N^2 (see Equation (3)) where Ω is now the local vertical component of the planet's rotation vector. The value of Θ at the latitude of the GRS should be close to Θ_R and the local value of N^2 should reach a

minimum at the longitude of the GRS. The former result could be consistent with the absence of a large eddy comparable to the GRS at similar northern latitudes on Jupiter, since very small asymmetries in the net heating etc. between the two hemispheres could result in Θ exceeding Θ_R at higher latitudes in the northern hemisphere than in the southern hemisphere. We note also the property of intransitivity revealed by the laboratory experiments (see above), implying that a pattern of flow that includes two or more regularly spaced eddies identical to the GRS may also be possible under the conditions now prevailing at the latitude of the present GRS (cf Figs 7(b) and 7(c)).

At first sight it might seem remarkable that dynamically similar phenomena can be produced on scales differing by such a large factor, but quite general considerations of dynamical processes that produce baroclinic eddies have accounted for this similarity. Central to these considerations is the recognition that the flow in the main body of the fluid, outside the boundary layers at the top, bottom and sides, is quasi-geostrophic and therefore satisfies the so-called "potential vorticity equation"

$$\frac{D}{Dt}\left\{\nabla^2\Psi + f^2\frac{\partial}{\partial z}\left[\frac{1}{N^2}\frac{\partial\Psi}{\partial z}\right]\right\} - \frac{\alpha}{r}\frac{\partial\Psi}{\partial\phi} = 0, \qquad (4)$$

which must be solved under appropriate boundary conditions, with acceptable solutions matching the viscous and thermal boundary layers present at the axial and radial extremities of the fluid. Here Ψ is a stream function related to the vertically-averaged horizontal flow, ∇^2 is the horizontal Laplacian operator (so that $\nabla^2\Psi$ is the average z-component of relative vorticity), D/Dt is the substantial time derivative following the geostrophic motion, and $f = 2\Omega$. The term $-\alpha r^{-1}\partial\Psi/\partial\phi$ represents potential vorticity changes

associated with the combined effects of axisymmetric sloping endwalls and spatial variations in the vertical density stratification, where α depends on the values of the endwall slopes and the thermal structure of the flow. The term is roughly analogous to the so-called 'beta' term in the corresponding form of the equation used in dynamical meteorology and oceanography, where α is there taken as the rate of change with latitude of the vertical component of the Earth's rotation vector. An equation of this form governs many types of quasi-geostrophic flows, including slantwise convection, in systems ranging from planetary atmospheres and oceans with horizontal scales of thousands (and even tens of thousands) of kilometres, down to the laboratory apparatus used in the experiments described in the present paper. This remarkable result can be understood by noticing that the essential balance of terms in equation (4) is such that

$$\left|\frac{D}{Dt}\nabla'^2\Psi\right| \sim \left|\frac{D}{Dt}\left\{f'^2\frac{\partial}{\partial z}\left(\frac{1}{N^2}\frac{\partial\Psi}{\partial z}\right)\right\}\right| \gtrsim \left|\frac{\alpha}{r}\frac{\partial\Psi}{\partial\phi}\right|. \qquad (5)$$

This implies that $fL/NH \sim 1$ if L is a characteristic horizontal dimension associated with the term $\nabla'^2\Psi$, and H is a characteristic vertical dimension associated with the term $f'^2\partial(N'^{-2}\partial\Psi/\partial z)/\partial z$. For example, in the case of the Earth's atmosphere $L \lesssim 10^7\,m$, $f \sim 10^{-4}s^{-1}$, $N \sim 10^{-2}s^{-1}$ and $H \sim 10^4\,m$, so that $fL/NH \sim 10$. For typical laboratory annulus experiments $L \lesssim 10^{-1}\,m$, $0 < f < 10\,s^{-1}$, $0.1 < N < 1\,s^{-1}$ and $3\times10^{-2} < H < 3\times10^{-1}\,m$, enabling a wide range of values of fL/NH to be achieved, from zero up to ~ 300. This includes

values typical of planetary atmospheres. For the South Tropical Zone of Jupiter, where the GRS occurs, $L \sim 10^7\,m$ and $f \sim 10^{-4}s^{-1}$; this implies $NH \sim 10^3\,ms^{-1}$ if for quasi-geostrophic disturbances we have $fL/NH \sim 1$. This value of NH is consistent with what little is known about the deep vertical structure of Jupiter's atmosphere. The 'alpha' term $-\alpha r^{-1}\partial\Psi/\partial\phi$ in equation (4) can modify slantwise convection quantitatively, by changing the azimuthal and, in extreme cases, radial wavelengths of unstable modes and their rate of propagation relative to the mean flow, and altering the critical values of Θ at which axisymmetric flow gives way to non-axisymmetric flow. But there is ample evidence that the 'alpha' term does not preclude the existence of the regular non-axisymmetric regime of flow, which is a matter of some importance when applying the results of laboratory studies to atmospheric systems.

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LEGENDS FOR DIAGRAMS

Figure 1. Long-lived anticyclonic eddies in Jupiter's atmosphere, namely the Great Red Spot, which is about 20,000 km long and at least 150 years old (and may have first been seen by Robert Hooke in 1664), and one of the three White Ovals that were seen to form in 1939. The arrows give the sense of relative motion. The "wind" speeds, as determined by Dr R F Beebe of the New Mexico State University, are given in kilometres per hour. For comparison note that points on Jupiter's equator rotate at about 35,000 km per hour. The very existence of these long-lived eddies has important implications for theories of atmospheric predictability. There is no generally accepted explanation of the eddies but the experiments illustrated in Figures 2 and 3, 6 and 7 indicate one possible line of attack.

Figure 2. Streak photographs giving one example of the top-surface flow pattern in each of the three main modes of thermal convection in a rotating fluid annulus subject to axisymmetric heating at the outer side-wall and cooling at the inner side wall, according to experiments first carried out by the author in 1950. The character of the motion depends on a number of parameters involving the acceleration of gravity, dimensions of the apparatus, thermal coefficient of cubical expansion, viscosity and thermal conductivity of the working fluid, etc. In an experiment in which Ω, the angular speed of rotation of the whole apparatus about its vertical axis of symmetry, is the only quantity varied, axisymmetric flow is found at low values of Ω (see

I). At intermediate and high values of Ω the flow is non-axisymmetric, with well-developed jet streams (cases II and III). At intermediate values the non-axisymmetric flow is regular - i.e. spatially and temporally periodic, with wavenumber ranging from 2 to 5 (for the geometry shown) as Ω increases. Such regular flow are exemplified by case II, where the wavenumber is 3 and there is little tendency for the flow to "vacillate", so that the pattern is effectively steady apart from an angular drift at constant speed relative to the walls of the apparatus. At high values of Ω (see case III) the flow is highly irregular; this chaotic motion is an example of what meteorologists concerned with large-scale motions in the Earth's atmosphere have termed "geostrophic turbulence". A wide variety of fluid dynamical and other non-linear systems are now known to exhibit either ordered or chaotic behaviour depending on the impressed conditions, and important unifying theoretical concepts are now beginning to emerge.

Figure 3. Numerical simulation of the top-surface flow pattern (Figure 3b) of thermal convection in a rotating fluid annulus subject to internal heating, with cooling taking place at both side-walls, as produced in laboratory apparatus (Figure 3a). Conditions are such that the flow is non-axisymmetric and regular with principal azimuthal wavenumber 4 (cf. Figure 2 case II) and little vacillation; that is to say the flow consists of 4 virtually identical steady eddies each circulating in an anticyclonic sense at the upper level, with horizontal motion largely confined to a peripheral jet stream. Recent studies of the structure, stability and energetics of such eddies

strengthen the proposal that they are dynamically similar to the long-lived eddies in the atmospheres of Jupiter and Saturn, such as the Great Red Spot and three White Ovals illustrated in Figure 1b. Of particular importance in this connection is the discovery that close to the transition to axisymmetric flow, the regular non-axisymmetric flow can be characterized by the presence of a single isolated compact eddy (see Figures 6 and 7).

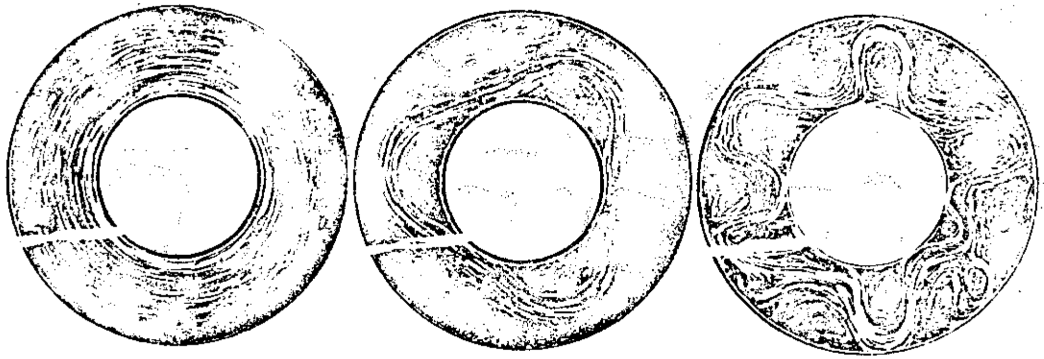
Figure 4. Illustrating the principle of the method introduced by the author in 1978 for finding the radius r_c of the electrically-conducting fluid core of a planet in which magnetohydrodynamic dynamo action is taking place (see Hide (1981) and Benton (1983)). $N(S;t)$ (see full lines) and $N(S;t+\Delta t)$ (see dashed lines) measure the total number of intersections of magnetic lines of force with a general spherical surface S well above the core at epochs t and $t+\Delta t$ respectively, and $\dot{N}(S;t)$ is the time rate of change of $N(S;t)$. The corresponding quantities evaluated at the surface of the core are $N(S_0;t)$, $N(S_0;t+\Delta t)$ and $\dot{N}(S_0;t)$. Whilst $N(S;t)$ varies on the time-scale of the motions in the core that produce self-exciting dynamo action, $N(S_0;t)$ varies on the much greater time-scale of ohmic decay, which is about 10^4 years for the Earth and possibly very much longer for Jupiter and Saturn. The value of r_c can therefore be determined from detailed measurements of secular changes in the magnetic field in the accessible region near or well above the surface of the planet by finding, by downward extrapolation from the measurements, that surface S_0 for which temporal changes in $N(S_0;t)$ are effectively

negligible (on the secular variation time-scale). The method has been well tested by applying it to the Earth, for which it gives the liquid metallic core radius to within 2% of the value determined by the more accurate methods of seismology. It will therefore be possible in due course to apply the method with confidence to Jupiter, Saturn and other magnetic planets when, as a result on future missions such as Project Gailieo, more is known about the structure and time variations of their magnetic fields.

Figure 5. View of Saturn from Voyage 1, from a distance of more than 5×10^6 km, four days after the encounter in November 1980 (see Science, 1982, 215, No. 4532) (figure courtesy of NASA).

Figure 6. Thermal convection in a rotating fluid annulus subject to internal heating, with cooling taking place at both side-walls (see Figure 3). Conditions are such that the flow is non-axisymmetric and regular with principal azimuthal wavenumber $m = 1$. The flow field near the upper level exhibits an isolated baroclinic eddy which undergoes no significant time variation, apart from a steady drift relative to the walls of the apparatus. Figure 6a is a streak photograph (streak duration 10s) of flow in laboratory apparatus and Figure 6b) shows the field of horizontal velocity vectors derived from a. Figure 6c gives the "eddy stream function", defined as the total stream function with the azimuthal mean component removed, obtained from b; negative contours are dashed. (After Read and Hide (1984).)

Figure 7. Panel (a) is a mosaic of Voyager 1 images of Jupiter, projected to show the planet as seen from the south pole. Latitude lines are concentric circles centred on the pole, which lies within the black jagged area (due to missing data) at the middle of the frame. The long-lived anticyclonic atmospheric eddies appear (apart from the GRS at top right) as trains of white ovals on lines of constant latitude. Panels (b) to (f) are upper-level streak photographs of flow in the laboratory apparatus (see also Figures 2, 3 and 6) at various values of Θ within the range $\Theta_R > \Theta > \Theta_I$ (see equation 1) showing slantwise convection manifested as steady regular baroclinic eddies in a rotating fluid subject to internal heating and sidewall cooling. (b) shows an isolated single eddy ($m = 1$, compare Figure 6(a)) at $\Theta = 2.92$; (c) $m = 2$, $\Theta = 2.84$; (d) $m = 3$, $\Theta = 2.16$, (e) $m = 4$, $\Theta = 0.72$; (f) $m = 5$, $\Theta = 0.48$. The mean radius of the planet Jupiter is 6.97×10^7 m, nearly 10^9 times the outer radius of the annular convection chamber in the laboratory apparatus (10^{-1} m), but, as shown in the text, the appropriate dimensionless dynamical similarity parameters are comparable.



(I) symmetric ($\Omega = 0{\cdot}341$ rad s^{-1})

(II) steady waves ($\Omega = 1{\cdot}19$ rad s^{-1})

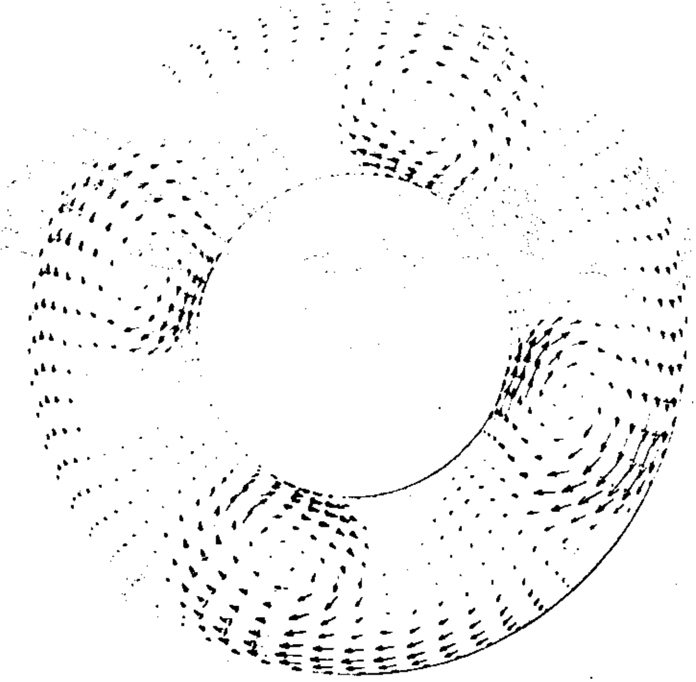
(III) irregular ($\Omega = 5{\cdot}02$ rad s^{-1})

FIG 2

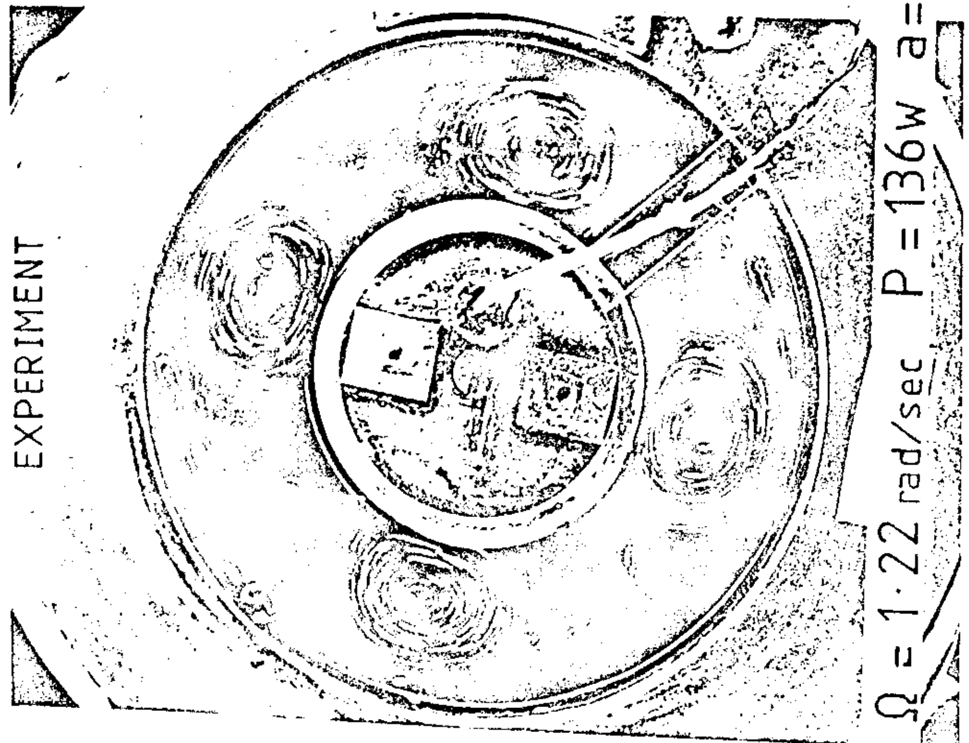
FIG 1

Baroclinic Waves In An Internally Heated Fluid Annulus

NUMERICAL SIMULATION



EXPERIMENT



$\Omega = 1{\cdot}22$ rad/sec P = 136w a = 4·06cm b = 8·55cm d = 12cm

FIG 3

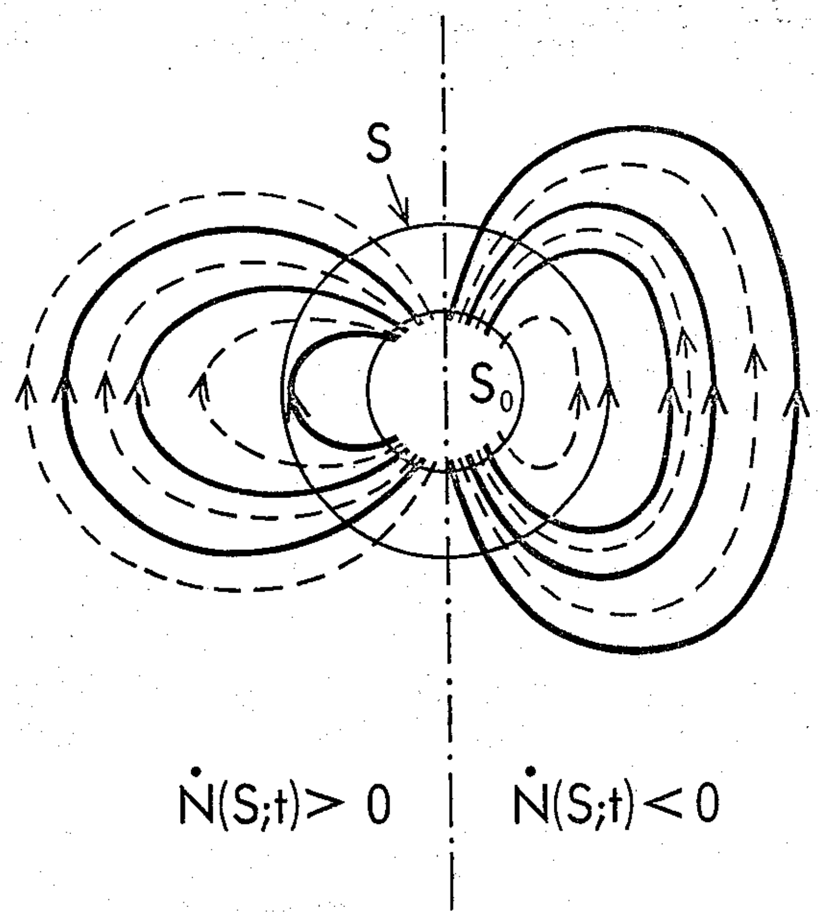


FIG 4

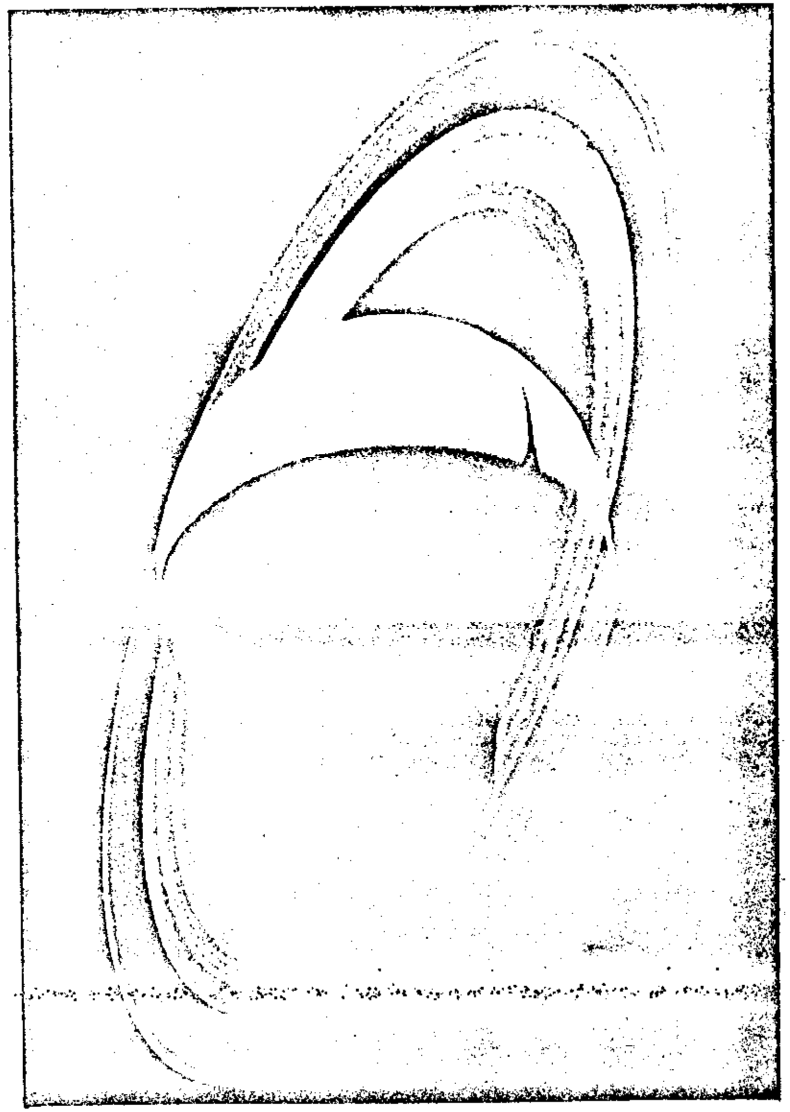


FIG 5

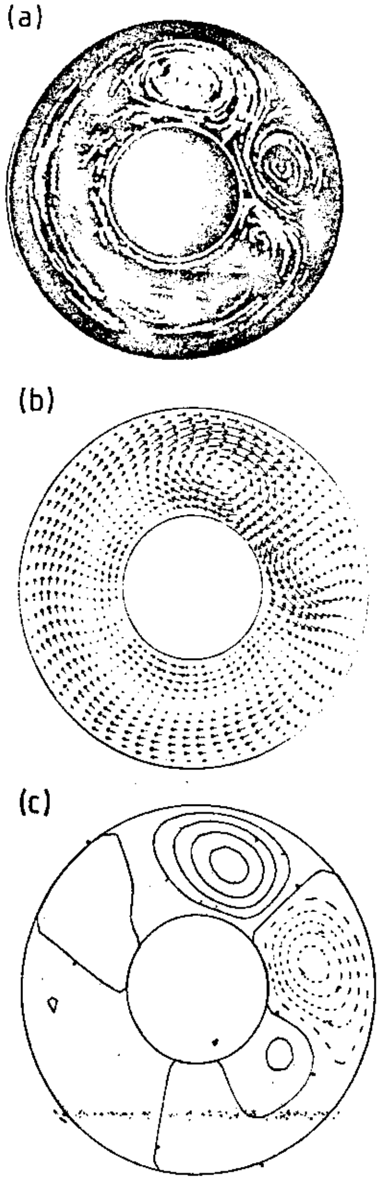


FIG 6

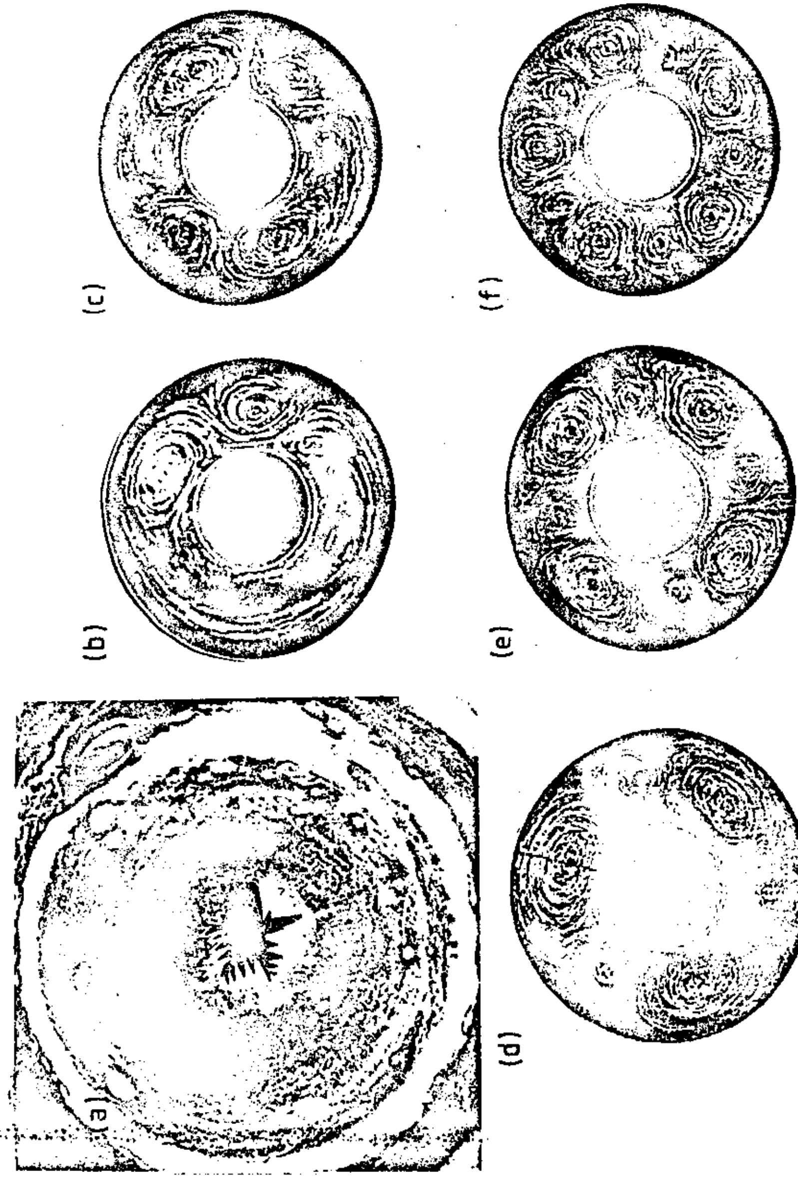


FIG 7