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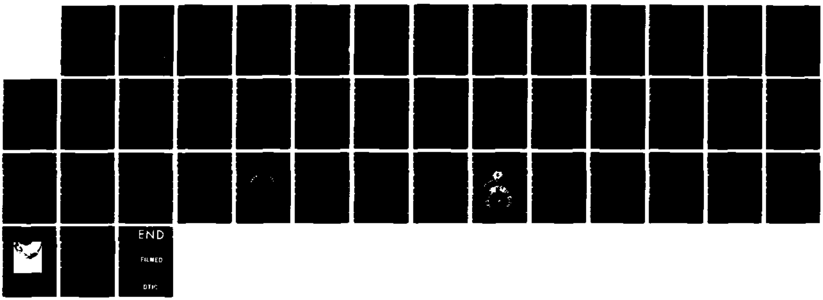

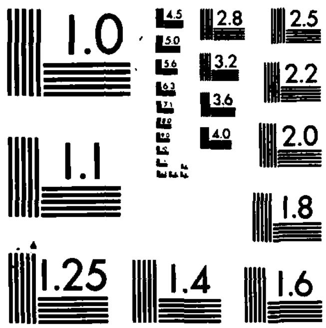

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by

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SUMMARY

This is the written version of the Milne Lecture for 1984, delivered at the Mathematical Institute, University of Oxford, on 1 November 1984. It is to be published in the Quarterly Journal of the Royal Astronomical Society.

The Lecture offers a superficial survey of the modern view of the Earth's atmosphere, followed by samplings of past ideas between BC 350 and AD 1925.

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1. INTRODUCTION

Most previous Milne Lecturers have been either friends or pupils of E. A. Milne, but I cannot claim any such connection, although I did once hear him lecture on kinematic relativity when I was an undergraduate, and was much impressed. My link with Milne in this lecture is through the subject matter, for Milne[1, 2] propounded several new ideas about the Earth's atmosphere - now transformed to old ideas by the passage of time.

My aim is to look at the Earth's atmosphere in its entirety, the Sphere of Air as the ancient Greeks called it. To set the scene, I shall outline modern views rapidly and superficially, and then offer some snapshots of past ideas. The air near the ground has always been familiar to people down the ages, so I shall not say much about the lower levels of the atmosphere but concentrate on the general picture.

I chose this subject because I feel that 'this most excellent canopy the air', as Hamlet called it, is unjustly underrated by those whose lives depend on it. Deprive us of air for even a few minutes and we should all be dead. Without it, life on Earth would either never have evolved or would have taken a quite different course. We are the creatures of air. Yet we just take it for granted. But why? The Moon has no air: how do we know that the Earth's air will not also escape into space? This is the very problem that occupied Milne.

Its power to keep us alive by letting us breathe is one great virtue of the atmosphere. But it has another virtue equally vital: it is transparent to sunlight, thereby allowing the photosynthesis on which our food depends. And even those astronomers whose thoughts are on higher things than breathing or eating should not curse the atmosphere for degrading their images but instead salute it for kindly allowing the stars to shine: otherwise astronomy would have been strangled before birth.

When our attitude towards the Air is so offhand, it is not surprising to find that we are even more cavalier in our attitude towards the history of ideas about the atmosphere. Though historical scholarship on almost every conceivable subject has multiplied greatly in the past thirty years, there is, as far as I am aware, no book surveying the history of ideas about the atmosphere down the ages. This is in stark contrast with the many, many, books about the history of ideas in astronomy: the ideas of Copernicus, Kepler and Galileo are all widely known. (Perhaps it is because the air controls our every-minute life, while astronomy has no effect on every-day life and is therefore a 'purer' subject?) Meteorologists might be expected to take some interest in the air, but they seem to have been too busy forecasting to bother much about looking backwards: in the UK it was not until 1983 that the Royal Meteorological Society set up a history section.[3] And even the meteorologists concentrate their attention on just a tiny fraction of the atmosphere, the lowest levels.

There is not even a name for the study of the atmosphere. 'Aeronomy' is available, and there is an International Association of Geomagnetism and Aeronomy; but in practice 'aeronomy' usually refers to the chemistry and electrodynamics of the upper atmosphere.[4] The Air would have a much better image today if there had been in the UK a Royal Aeronomical Society to match the Royal Astronomical Society. What happened was that in the 19th century the meteorologists were inevitably dominant among atmospheric scientists, and they pursued their specialism, leaving the Royal Astronomical Society to look after the higher reaches of the atmosphere, the realm of the aurora and (ironically) of meteors. The astronomers cannot be expected to be dedicated aeronomists. So, in the UK and many other countries, the science of the Air has provided a painful illustration of the maxim that organisms rarely function well when split into two parts.

2. THE MODERN VIEW OF THE ATMOSPHERE

Because of its transparency I cannot give a useful picture of the atmosphere at optical wavelengths by day, but the situation is different at night. Looked at from space, the atmosphere then often shines quite brightly in regions near the magnetic poles, where charged particles of high energy excite fine displays of the aurora at heights of 100 km upwards. Fig. 18 shows a moderate aurora over Canada, with the city lights of the USA below seeming quite puny by comparison: indeed the power in a strong aurora can reach 10^7 MW, more than the total world electricity supply.

Our perception of the aurora has been much enhanced by these views from space: from the ground it can very rarely be seen at the low latitudes where most people live, and at high latitudes the weather is usually either too cloudy or too cold to encourage casual night sky-watching. A strong auroral display, changing in form and colour every few seconds and covering most of the sky, is a most beautiful and impressive sight. Several recent books[5, 6, 7] give splendid colour photographs but cannot capture the dynamic qualities. There are many poems about the aurora,[5, 6] and I quote a few lines which concentrate on the rapid movements rather than the colours:

> We watch the airy curtains flicker back and forth,
> See the sudden searchlights stab up and die,
> Column after ghostly column balanced in the sky.

Pale electric atom-streams shooting from the Sun
Have felt the Earth's magnetic might
And spiralled in to beautify the night.[8]

To return from poetry to science, the chief scientific parameters that describe the atmosphere are the temperature T, pressure p and density ρ, and they are connected by the well-known gas law,

$$\frac{p}{\rho} = \frac{RT}{M}, \tag{1}$$

where R is the gas constant (8.31 J K^{-1} mol^{-1}) and M is the molecular weight of the gas. The decrease of pressure with height y is given by the hydrostatic equation,

$$\frac{dp}{dy} = -\rho g, \tag{2}$$

where g is the acceleration due to gravity. Eliminating ρ between equations (1) and (2), we have

$$\frac{dp}{p} = -\frac{Mg}{RT}\,dy. \tag{3}$$

Thus, if we assume RT/Mg is constant and denote it by h, which is called the 'scale height', equation (3) may be integrated to give the variation of p with height as

$$p = p_o \exp\left(-\frac{y-y_o}{h}\right) \tag{4}$$

where p_o is the pressure at a chosen reference level, $y = y_o$. If we further assume that the Earth is spherical of radius r_E, with an inverse-square gravity field, the variation of density ρ with height can be written

$$\rho = \rho_o \exp\left(-\frac{y-y_o}{H}\right), \tag{5}$$

where H, defined by the equation

$$\frac{1}{H} = \frac{1}{h} - \frac{2}{r_o}, \tag{6}$$

is called the 'density scale height'. In equation (6), $r_o = r_E + y_o$ and is the distance from the Earth's centre at height y_o. The assumption that h is constant implies that H is also constant; and since $h \ll r_o$, equation (6) shows that the difference between H and h is never more than a few per cent. Equation (5) is not exact, but the error is negligible: the right-hand side should be multiplied by a factor $\{1-(y-y_o)^2/r_o^2\}$, which departs from 1 by less than 2.5×10^{-4} if $(y-y_o) < 100$ km.

Equations (4) and (5) cease to apply when the height becomes so great that the mean free path of the air molecules exceeds h, and in practice the equations begin to lose accuracy at heights above about 500 km.

Although in reality RT/Mg is not quite constant, equations (4) and (5) provide powerful approximations, because we can usually divide the atmosphere into height bands thin enough to ensure that RT/Mg is nearly constant. The equations tell us that if the temperature T is higher, the pressure and density both fall off more slowly with height, because h and H are larger. The density falls off by a factor of 2.718 whenever the height increases by H, or by a factor of 20 for an increase of 3H. For example, if H = 33.3 km and y_o = 200 km, the density at y = 300 km would be $\rho_0/20$ and at 400 km would be $\rho_0/400$. If the temperature at heights above 200 km were to increase by a factor of 2, the value of H would increase to 66.6 km and the density at 400 km would be $\rho_0/20$. Thus if ρ_0 stays nearly the same, doubling the temperature produces an increase in density at a height of 400 km by a factor of 20; and in general higher temperatures imply higher densities - usually much higher densities - for heights above 200 km.

At heights above about 100 km, diffusive equilibrium prevails, and equations (4) and (5) can be applied to the individual species of gases in the atmosphere. For a given temperature T, the gases of lower molecular weight M have larger scale heights, because h = RT/Mg, and this confirms the intuitive belief that the lightest gases should rise to the highest reaches of the atmosphere -

Where lighter gases, circumfused on high,
Form the vast concave of exterior sky,

as Erasmus Darwin[9] expressed it in 1791.

As the temperature largely controls the rate at which pressure and density decrease, the variation of temperature with height,[10, 11] shown in Fig 1, is of crucial importance. The average temperature drops quite steadily from 290 K at sea level to about 220 K at a height of about 10 km and then remains fairly constant in the stratosphere up to a height of about 25 km. Then the temperature rises to a maximum of about 280 K at a height of 50 km, because of the solar ultra-violet radiation being absorbed by ozone. Above that, the temperature falls again in the upper mesosphere to a minimum of about 180 K at a height of 85 km. Above 90 km, the temperature increases sharply as a result of the more extreme ultra-violet radiation from the sun being absorbed, and this is the region known as the thermosphere, where at heights above 200 km the temperature becomes independent of height and has very high values. The temperature remains constant to heights above 500 km - indeed to as high aloft as the word 'temperature' remains meaningful. Above 500 km (for T = 1000 K) the mean free path of the atoms exceeds h, and many atoms pursue ballistic trajectories rather than continually colliding. Some escape, some collide, some fall back.[4]

At heights above 200 km, the atmosphere is controlled mainly by the Sun, which has two quite different effects.[10] First, the thermospheric temperature is much higher during the afternoon than in the early hours of the morning, an effect not unfamiliar at ground level: the minimum temperature occurs at about 3 am and the maximum at about 3 pm (though the times vary with latitude and season). The maximum. Even larger factors arise when the two variations are combined: at a height of 600 km, the density by day at the end of 1957 was 250 times greater than in 1964 at night.

So there are immense regular variations in density. But there are also intense short-lived variations, and Fig 4 shows a typical change in density in response to transient solar activity.[13] A solar storm occurred, disrupting the Earth's magnetic field, and the density at a height of 180 km (where density is relatively insensitive to solar activity) increased to nearly double in a few hours. At heights of 600 km the density can increase transiently by a factor of up to 8 in response to outbursts of solar activity.[14]

In addition to these short-lived variations there is another important longer-term irregular effect, the semi-annual variation. In a normal year the density has maxima during April and October, and minima during January and July: Fig 5 shows the variation of density in 1972, after correction for geomagnetic and day-to-night effects.[15] The density in October exceeded that in late July by a factor of about 1.5 in the example shown in Fig 5, and this is at a height of 250 km. The factor increases to about 3 at heights near 500 km, and then decreases at greater heights.[16] The semi-annual variation probably originates from seasonal variations in the lower atmosphere, but full details have not yet been established. The strength and the timing of the oscillation vary appreciably from year to year,[15, 16] but the example shown in Fig 5 is fairly typical, and also illustrates the random-seeming variations of 5-10% on time scales of about a week, which characterize the behaviour of air density.

These are four important world-wide variations in upper-atmosphere density. I am ignoring many other effects that are confined to particular times, heights or localities, such as the 'winter helium bulge', propagating gravity waves and dynamical effects in the auroral thermosphere. There are several recent atmospheric models[17-19] in which these effects are discussed or evaluated.

Most of the irregular variations in the upper atmosphere can be blamed on solar disturbances. To see why, we need to take a wider view.[20] The Sun is a hot ball of gas stuck in the midst of a vacuum, and an obvious response to this situation is that it might pour out its substance into interplanetary space. This is exactly what it is doing - just bleeding away really, though quite slowly, fortunately for us. Charged particles, mostly protons and electrons, stream out from the Sun at speeds of about 400 km/s when the Sun is quiet; but when the Sun suffers a convulsive eruption on its surface, the particles shoot out much faster in a plume. The solar wind, as this outpouring is called, sweeps across the Earth's orbit, and we are protected from its full effects by the outer regions of the atmosphere, the magnetosphere as it is called, which when looked at from the outside is like a huge tadpole-shaped cavity in the solar wind.

variation is by a factor of about 1.3, so that if the minimum night-time temperature, T_N, is 1000 K, the temperature at 3 pm will be near 1300 K. The second effect is the control exercised by the Sun via its extreme ultra-violet radiation. This varies greatly during the 11-year cycle of sunspot activity, and consequently the night-time temperature is very much lower in a year of sunspot minimum such as 1975 (when $T_N = 600$ K) than at sunspot maximum: in 1981, for example, $T_N = 1000$ K. These are the kinetic temperatures, but the air at such heights is so nearly a vacuum that the air temperature has no appreciable effect on a solid body like a satellite, the temperature of which is controlled by the radiant heat of the Sun, or its absence, and also by the reflectance of the satellite's surface.

As we have seen, the scale height depends on the molecular weight - in other words, on the atmospheric composition - as well as the temperature. There is mixing of the gases up to a height of about 100 km; above that the gases begin to sort themselves out according to their molecular weights.[10] Nitrogen remains dominant up to 170 km; then the main constituent is atomic oxygen, up to 500 km if the solar activity is low and the temperature is about 700 K. Helium takes over the leading role between about 500 and 900 km, and atomic hydrogen above that, as shown in Fig 2. For a higher thermospheric temperature, of 900 K, atomic oxygen predominates up to 650 km and helium from there up to 1800 km.

A more tangible atmospheric parameter than the temperature is the density, which directly controls the air drag felt by the satellites passing through the upper atmosphere. Density can be determined by measuring the drag on orbiting satellites,[12] and the results of thousands of such measurements are summarized in Fig 3, which shows the variation of density with height for heights between 150 and 1000 km.[10] The density scale is logarithmic: it is conveniently centred on the value 1 nanogram per cubic metre (that is, 1 gram per cubic kilometre). The density decreases by a factor of 1 million between the right and left edge of the diagram.

As well as the million-fold variation with height, two other substantial variations are evident in Fig 3. The first is a day-to-night variation in density, linked with the day-to-night temperature variation, though not exactly in phase with it. The density has a minimum at about 4 am and a maximum at about 2 pm. This large variation occurs regularly each day, with the maximum density being about 5 times greater than the minimum at heights near 500 km. The factor of variation is smaller at lower heights, as Fig 3 shows, but remains large at heights up to 1000 km when solar activity is high. The second major variation, even greater than the first, is that due to solar activity. This effect increases with height up to about 600 km, with the density at an average sunspot maximum (such as that of 1968-70) exceeding the density at sunspot minimum by a factor of about 3 at 250 km height, a factor of about 8 at 400 km and about 20 at 600 km. However, these factors are even greater for a strong solar maximum - about 3.5, 12 and 60 respectively for 1957-8, and about 3.2, 10 and 40 respectively for the 1981

Figure 6 shows a rather outdated sketch of the magnetosphere which serves to indicate the main features. The magnetosphere acts as an obstacle in the strong outflow of particles of the solar wind, and a shock wave develops, quite like the shock wave arising when a spherical obstacle is placed in a supersonic wind tunnel - except that this shock wave at the boundary of the Earth's atmosphere is at ridiculously low pressures, and is a magnetohydrodynamic rather than an ordinary aerodynamic shock. When the Sun is quiet and the solar wind is blowing steadily, most of it flows round the boundary and we are protected from it. But when there is a solar flare or other strong disturbance, the higher-energy particles find their way into the magnetosphere. Some particles enter through the polar cusps, but most of them make their way in via the tail of the magnetosphere. From either point of entry they tend to follow the lines of magnetic force and therefore impinge on the Earth's atmosphere mainly at latitudes about 20-30° away from the magnetic poles, thus producing either visible aurorae or invisible but quite vigorous disturbances in the polar thermosphere. What I have said is of course a great over-simplification: magnetospheric physics is now virtually a branch of science of its own, and the 'meteorology' of the magnetosphere is an extremely complex subject.[21, 22]

Any attempt to give a picture of the atmosphere is likely to leave the impression that it is static, like a picture: that is a false impression. The magnetosphere is not only rather like a tadpole in shape, but also wriggles vigorously, though more slowly than a tadpole, in response to the continual fluctuations in the flow of particles from the Sun. The air at lower levels in the atmosphere is also restless and dynamic: there are winds of more than hurricane force, driven by the great variations in pressure and density which I have already described. In the thermosphere the wind speeds can exceed 500 m/s, especially in the auroral zone during disruptions due to solar storms.[23] And we find regular daily variations in the winds at lower latitudes by up to 200 m/s: for example,[24] at heights near 300 km, there are west-to-east winds of up to 150 m/s in the evening, and east-to-west winds (though not so strong) in the morning.

That concludes my quick survey of modern ideas on the atmosphere: as well as being superficial, the survey is also biased because it is designed so as to throw light on the historical topics ahead.

3. THE INFLUENCE OF ARISTOTLE

Now I jump back more than 2000 years to look at some of the old ideas of the atmosphere. First, a word of apology: I shall limit myself to European culture. It would be interesting to make comparisons with early ideas in other cultures, but that would lead to far more material than would fit into a single lecture.

I begin with Aristotle, whose ideas had so much influence over this University during its first 400 years. Aristotle's book called Meteorologica, written about 350 BC, dominated western European thought about the atmosphere until 1600 AD, so we ought to stop and look at it. Your first thought may be to blame Aristotle for the disgustingly long word 'meteorological', that heptasyllabic millstone round the neck of its practitioners. Strangely enough, however, Aristotle does not seem to have been responsible for coining the word. Figure 7 shows the first chapter of his book,[25] and in the passage underlined he says he will discuss the subject 'which all our predecessors have called meteorologia'. He also says that the word covers 'everything that happens naturally', so that he deals with the entire realm of geophysics, all that is earthly rather than heavenly.

Aristotle's picture of the Earth and its atmosphere is in terms of the four spheres of Earth, Water, Air and Fire, Fig 8. Classical scholars are often scornful about this picture. Indeed the translator of the Meteorologica, H.D.P.Lee, remarks in his preface that the book is little read because 'Aristotle is so far wrong in nearly all his conclusions that they can ... have little more than a passing antiquarian interest'.

But is Aristotle wrong, or is he making a good first approximation? Aristotle is certainly correct in taking the solid Earth as the central sphere. He is also right to suggest that this is nearly covered by a sphere of Water, the hydrosphere as it is often called today. Though we now know that the oceans cover nearly 75% of the Earth to an average depth of 5 km, Aristotle himself lived in a region where land was dominant: so he did well to avoid being misled. Above the water comes the sphere of Air: no one will quarrel with that. The air at the lower levels - the air we breathe - is usually quite cool and often humid. But, as we have already seen, the upper regions of the atmosphere, above 200 km, have dynamic temperatures ranging between 600 K and 1500 K, much higher than any domestic oven; we call this the thermosphere, so why should we blame Aristotle for calling it the sphere of Fire? Beyond that in Aristotle's picture is the celestial region, which is of course divided into further spheres belonging to the Sun, Moon and planets. However, if we take the outermost sphere as that of the Sun, the sphere of Fire melts easily into it and the boundary can be looked on as the boundary of the magnetosphere. Aristotle says that 'the celestial region as far down as the Moon is occupied by a substance which is different from air and fire, but which ... is not uniform in quality'. By a slight stretch of the imagination we can identify that as the solar wind - and this is not really stretching the interpretation too far, because Aristotle does regard the sphere of Fire as being linked with the Sun's heat.

I must confess that I am hostile to Aristotelian physics in general, so it is rather unnerving for me to have to declare, misquoting Mark Antony -

Friends, Oxonians, and countrypeople,

I come to praise the Stagirite, not to bury him.

My 'conversion', even though strictly limited in scope, would no doubt have pleased the medieval scholars of this University.

Aristotle believed that the heat of the Sun drew up two sorts of 'exhalations' from the Earth, a hot dry exhalation, leading to thunder and lightning, shooting stars and the aurora; and, secondly, warm moist vapours, which cool and turn into clouds and rain and other 'watery meteors', as they were called. The aurora he regarded as having its home in the sphere of Fire, which is essentially correct if we equate that with the thermosphere. His division of the celestial sphere into shells housing the planets, Sun, Moon, etc, is shown in Fig 9.

For my next dip into the past, I visit the medieval and Renaissance scholars, not only at Oxford but at any other of the seats of learning in Europe. And we find that Aristotle still rules: more than 125 editions of the Meteorologica were printed before 1600, and Aristotle's model is illustrated again and again.[26] Fig 10 shows a version from a book[27] published in Paris in 1551. It is just the same really, except that the captions are in French.

But there was one refinement of Aristotle's model which seems to have gained general approval in the 16th century. The sphere of air was divided into three regions. The lowest was regarded as being heated by the Earth and was usually shown as cloudless. The second layer was colder, and this was where the clouds formed. The third level, the 'Suprema regio aeris', was heated by the Sun and by its proximity to the sphere of Fire, and so it was free of watery vapours. This cloudless upper region would correspond in our terminology to the stratosphere and above, and would merge into the thermosphere or sphere of Fire at its upper boundary. Fig 11 shows this tripartite atmosphere, as illustrated in a book by Finé[28] published in 1532. To us, Fig 11 seems unconvincing, because rain so often falls from the lowest layer. But there it is: they liked it. Many similar diagrams were published and have been collected by Heninger.[29]

Fig 12 shows another picture of the three-layer atmosphere, which appears[30] in the later editions of Reisch's Margarita Philosophica (first published in 1496). This diagram differs from Fig 11 by showing the Sun as actively in command and 'breathing' on the outermost regions of the atmosphere. The sphere of Fire is now no longer a complete sphere, but is very much under solar control, and has become roughly equivalent to the solar wind, with the 'Suprema regio aeris' now corresponding to the entire thermosphere. The idea that the Sun can be regarded as 'breathing out' the solar wind is quite appealing: but the metaphor fails because the Sun never breathes in; so the anthropomorphized solar wind has to be the bleeding Sun, rather than the breathing Sun. Nevertheless, Fig 12 is arrestingly similar to some 'cartoon versions' of modern concepts of the Earth in the solar wind.

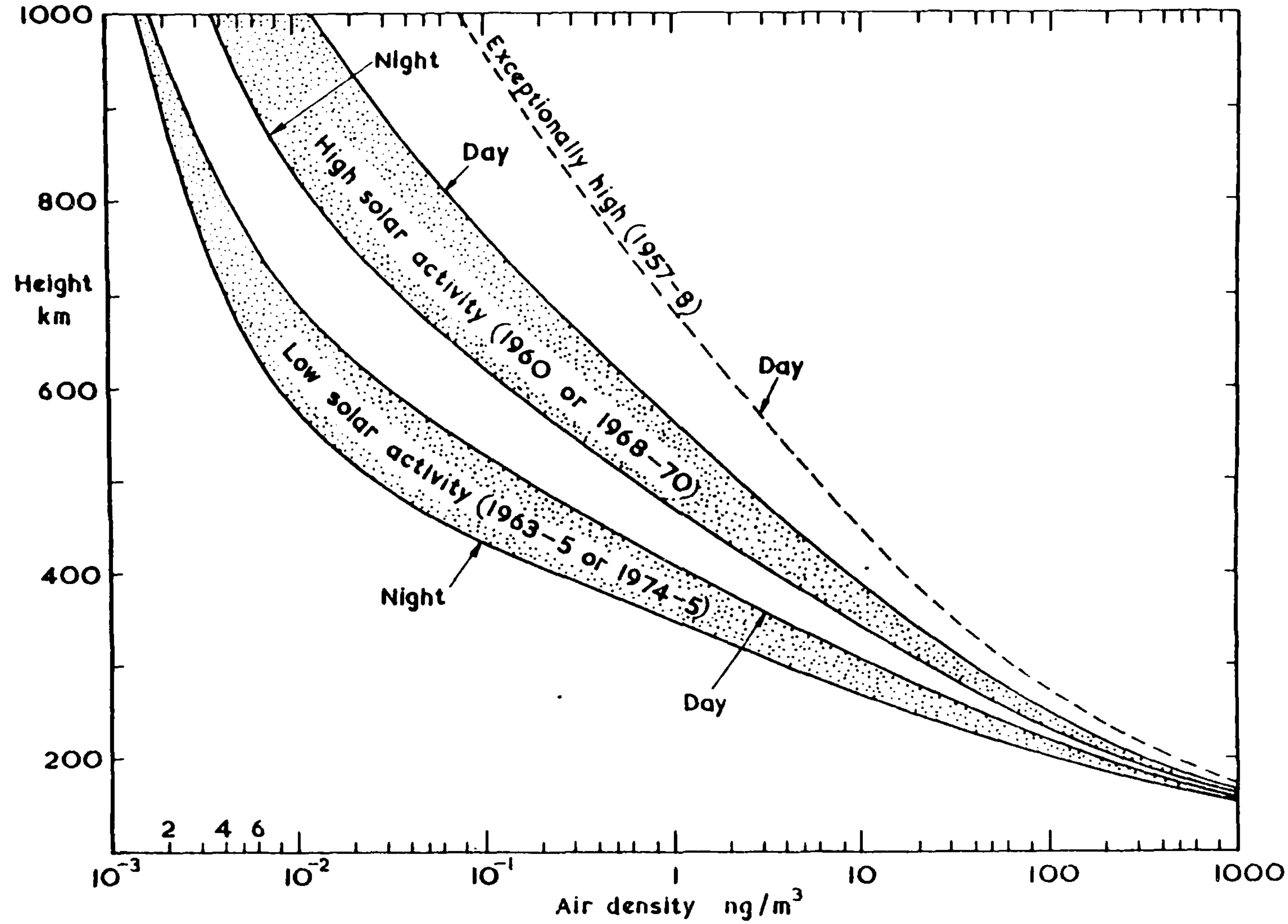

Fig 3 Variation of air density with height from 150 to 1000 km for high and low solar activity. Based on CIRA 1972

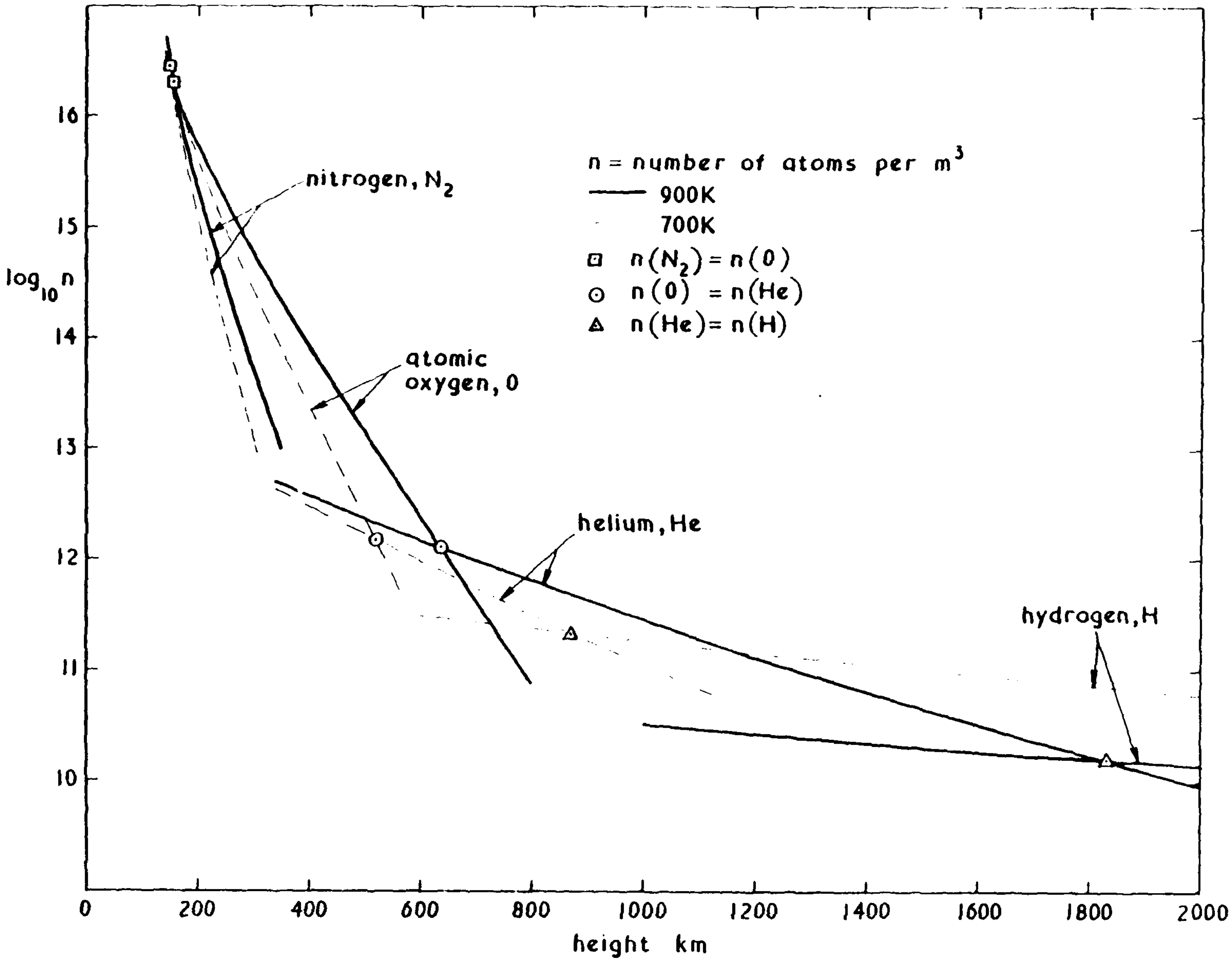

Fig 2 Concentrations of nitrogen, oxygen, helium and hydrogen, from CIRA 1972

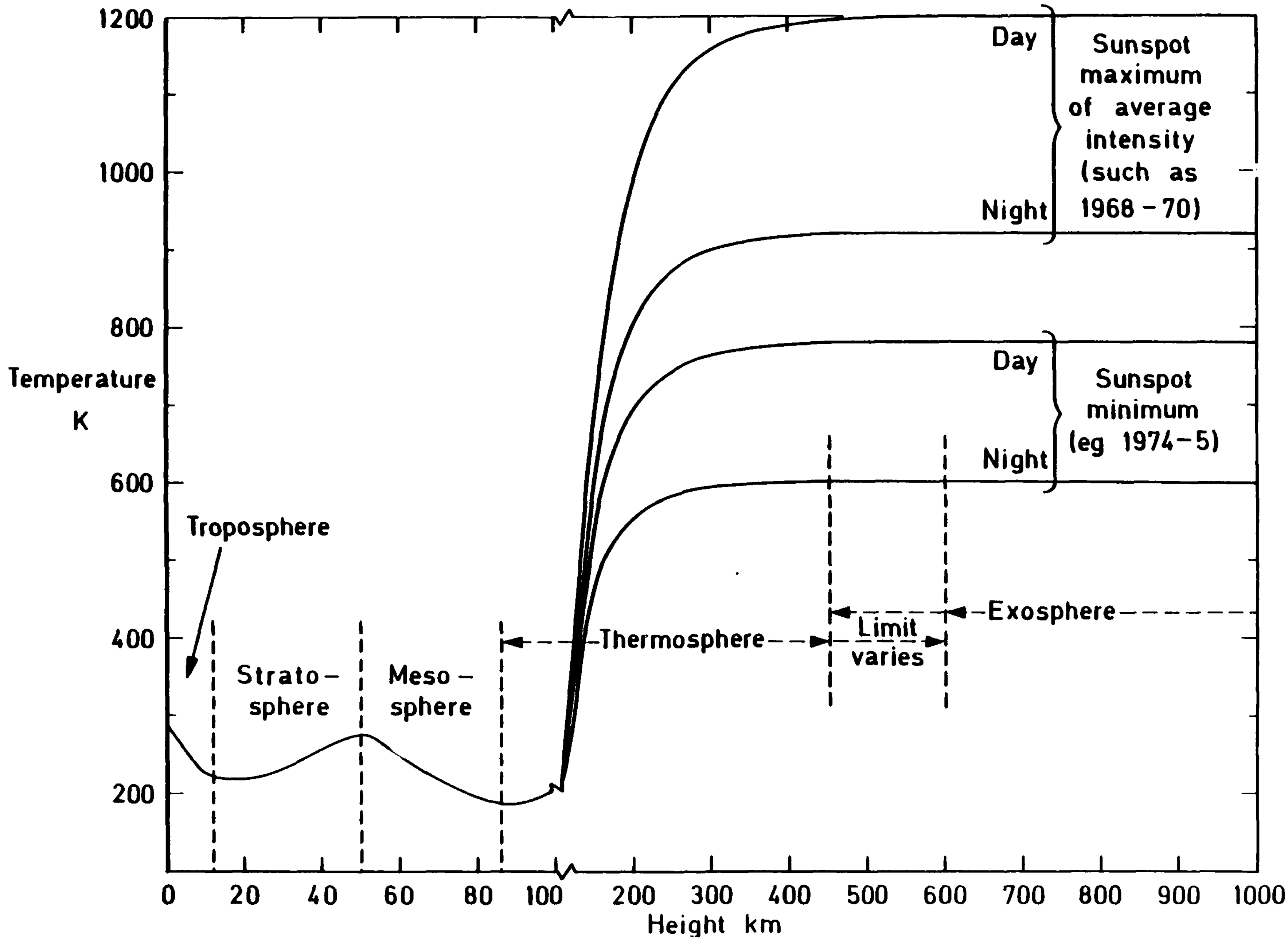

Fig 1 Average air temperature from sea level to 1000 km, from CIRA 1972

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that are securely established, and others where errors may be rampant. For example, no one is going to prove that the Earth is flat; its sea-level shape is now known correct to 2 metres all round. But current ideas on the composition and character of the Earth's deep interior, which no one has yet seen, might be overturned completely in the next 30 years, just as the ideas of Jeans, Chapman and Milne on the outer atmosphere were overturned within 30 years. The same scepticism may be needed in some areas of astronomy.

Science can be defined as the thought-system favoured by the majority of current scientists. If you think differently, you are an independent thinker, not a scientist, and papers that you write will probably be rejected by scientific journals, which have a censorship system euphemistically called 'refereeing'. As in football, the referees are not necessarily good players, but they do know the rules. Having said that against the system, I must also say that most independent thinkers are wrong and some are quite nutty. But some are right, and they provide the framework for the orthodoxy of the next generation, as for example with Wagener and continental drift, once heretical but now orthodox. After these subversive thoughts, it is only fair to end by undermining myself with the warning, 'Don't believe all that your Lecturers tell you'.

whereas it is only a minor constituent up to 400 km in the real atmosphere.

It may seem surprising that after all these errors Chapman and Milne emerge with reasonable values for air density and its variation with height for heights between 200 and 800 km, as Fig 17 shows. Their luck came in because they arrived at nearly correct values for the scale height through making two errors, each by a factor of over 4, which happened to cancel out. At a height of 300 km they have an atmosphere with a molecular weight of 4.0 (almost entirely helium) and a temperature of 219 K. Thus they have T/M = 55, and a scale height h = RT/Mg = 51 km. At 300 km height in the U.S. Standard Atmosphere 1976 the molecular weight is 17.7 and the temperature 976 K, which also gives T/M = 55 and h = 51 km. Their good luck is perhaps even more improbable than Jeans's bad luck.

Milne returned to the subject in 1923 in his paper on the escape of molecules from an atmosphere.[2] Though he again used the low temperature of 219 K, the heights he calculated for the level where molecules can escape - the base of the exosphere as we should now call it - are reasonably realistic: 630 km for helium and 1400 km for hydrogen. The latter is too high, but chiefly because he takes Jeans's high value for the hydrogen concentration.

7. RETROSPECT

That completes my set of snapshots of past ideas of the atmosphere. It is up to you to conclude what you will from what I have said: I can only give my own views. I think the history of science sharpens our perceptions of the present in a revealing way, by making us see that presently-fashionable views about matters on the frontiers of knowledge in a particular subject may be partly or completely wrong - even when they have the highest authority, as with the results of Jeans, Chapman and Milne which I have mentioned. We also have to face the hard fact that old ideas may sometimes prove to have more of truth than more modern ones. When I was an undergraduate, it was widely believed[49] that 'captured interstellar gas' was falling into the Sun at high speed - a concept now completely reversed in the outflowing solar wind. Also it should be remembered that 'the general reader' is not much interested in well-established science, so that writers of popular-science books need a continual flow of imaginative new concepts, particularly in astronomy, to provide material for their new books. Many imaginative astronomers gladly create these concepts, which are then popularized by the popularizers and earn credit for the creators. The history of science is like an X-ray that cuts through meretricious trappings and lets us see the bare bones of the modern ideas, which may look much less impressive if perceived as 500-year-old bones re-dressed.

The history of science teaches us to be humble, and also to be very sceptical of theories currently in fashion on subjects that are still in a state of flux. I would not wish to be accused of undermining all science: there are many areas rapidly vanish. It was not long before Jeans's assumptions about hydrogen were challenged, and unfortunately this led to the wrong idea that there was no hydrogen at all in the upper atmosphere. What was wanted - but was not forthcoming - was a compromise between the extremes of zero and Jeans.

My last example is the important paper[1] by Sydney Chapman and E. A. Milne about 'The atmosphere at great heights', published in the Quarterly Journal of the Royal Meteorological Society in 1920. The theory in this paper is excellent, and in applying the theory to the real atmosphere Chapman and Milne insured themselves against error by giving results for four possible values of the height above which there is diffusive equilibrium - and below which there is mixing and constant composition. The four possible values give densities at 200 km and above which differ by a factor of up to 100, so it is possible to choose the best of the values. Since this is the Milne lecture, I will be indulgent and do just that, choosing the value 30 km (although the actual height where diffusive equilibrium begins is near 100 km). The Chapman-Milne curve of density versus height then goes right through the middle of the modern diagram, as shown in Fig 17, which is merely Fig 3 with an additional line. The sight of this may well provoke applause for Chapman and Milne from all sides.

But their correct result, far from being a stroke of genius, was only luck, because they made four serious errors.

First, they assumed there was no hydrogen at all. Their comments are:

> Hydrogen is not indicated by the auroral spectrum, though this alone does not prove its absence.... The case when hydrogen is present has been sufficiently discussed by Jeans, and accordingly for the purposes of the greater part of this paper the absence of hydrogen will be assumed.

The absence of hydrogen explains the low density at heights near 1000 km in their model, but it is only a minor constituent below 500 km, so at lower altitudes their assumption of zero hydrogen was much better than Jeans's assumption of about 10^9 times too much hydrogen.

Their second error was the wrong choice for the height where diffusive equilibrium begins. Despite their 'insurance policy' of giving results for four different possible heights (12, 20, 30 and 50 km), all four were much lower than the 100 km which would now be recommended.

Their third error was to follow Jeans in assuming a constant temperature of 219 K, when we now know that the temperature ranges between 600 K and 1500 K in the thermosphere, with an average of about 900 K.

Their fourth error was to take the concentration of helium in the stratosphere too high by a factor of about 10^4. As a result of this error, helium, with molecular weight 4, becomes dominant in their atmosphere at heights of above 150 km, sphere at a height of 170 km - near the height where Halley was correct - has errors so huge as almost to defy belief, as Table 1 shows. Certainly Jeans was extremely unlucky: even if he had picked four numbers at random he would probably have done better.

Table 1 Number densities (per cubic centimetre) at 170 km height, from Jeans's *Dynamical Theory of Gases* and the *U.S. Standard Atmosphere, 1976*

Component:	Nitrogen	Oxygen	Helium	Hydrogen	
Jeans's value	350	3	1300000	182000000	all x 10^6
U.S. Standard Atmos:	10700	9800	17	$\simeq 0.2$	all x 10^6
Approx. error factor:	30	3000	80000	10^9	

Why was he so much in error? The first reason is his assumption about upper-atmosphere temperature. He says:

> We shall obtain a fair approximation to average conditions by assuming that the temperature [at] a height of 10½ km ... is -54°C (219° absolute), and that beyond this the atmosphere is in isothermal equilibrium.

So he assumed that the temperature was constant at 219 K, which is not nearly so good as Halley's tacit assumption that the temperature was the same as at sea level. Because of the low temperature, Jeans had much too small a scale height, and this explains why his value for the nitrogen concentration is too low by a factor of 30. The same error arises with oxygen, but the discrepancy is much greater because Jeans naturally assumed that the oxygen was diatomic, whereas in reality it is largely monatomic by 170 km height, although he could not have known this. Jeans's very high values for the concentrations of helium and hydrogen arise purely from taking much too large a sea-level value for both. In Jeans's atmosphere, hydrogen is dominant at heights above 70 km, which, like Erasmus Darwin's 60 km, is far too low. (However, it should be remembered that the concentration of hydrogen at 170 km height is not securely established and is subject to many variations: see Chapter 16 of the book by Banks and Kockarts.[4])

Jeans, although unlucky in applying his ideas to the real atmosphere, was one of the greatest applied mathematicians of his day, and he pioneered the theory of the escape of planetary atmospheres. He appreciated that at great heights the mean free path of the molecules becomes great enough for some of them to go into orbit or escape. And he developed a self-consistent theory for the escape rates of various species. He concluded that the escape rate even of hydrogen would be very low: at his assumed temperature of 219 K, hydrogen would take 10^{24} years to escape. But he does comment that if the temperature were 550 K, the escape rate would be 10^{18} times faster; so with a temperature of 1000 K all the hydrogen would

Halley's, gives this as a height of 60 km. Above that, he says,

> The common air ends, and is surrounded by an atmosphere of inflammable gas [hydrogen] tenfold rarer than itself. In this region I believe fireballs sometimes to pass, and at other times the northern lights to exist.[46]

He was correct in thinking that fireballs appeared in this region, and he quotes the height of the great fireball meteor of August 1783, which he himself observed, as 'between 60 and 70 miles' which is nearly right, and its speed as 'about 20 miles in a second'. But he wrongly thought that the smaller shooting stars were lower. He also placed the aurora in the correct region, as established some years later in measurements by Dalton.[6]

An interesting feature of Darwin's picture is his belief that the outermost atmosphere is formed of hydrogen, the lightest gas. He reached this conclusion from the simple idea that the lighter gases will rise to greater heights, although his height for the base of the 'hydrogen exosphere' is far too low - it should be at least 600 km. He also thought the presence of hydrogen was confirmed by the red colouring often seen in the auroras. 'It was observed by Dr Priestley', he says, 'that the electric shock taken through inflammable air was red.'[46] This was good thinking, but actually hydrogen only gives a very small proportion of the red colour in the aurora, because most auroral displays are at heights near 100 km, where there are only traces of hydrogen.

Darwin's picture was in many ways better than anything for 100 years. For example, later ideas about hydrogen were very confused and contradictory, as we shall see shortly. As another example, 90 years later, in the first International Polar Year of 1882, the stations for observing the aurora were set up too close together, because it was assumed that the aurora was about 8 km high.[47] As the actual heights are more than 80 km, these stations were wrongly situated for triangulation and the measurements were much less accurate than they would have been if Darwin's (or Dalton's) heights had been adopted.

6. JEANS, CHAPMAN AND MILNE

I shall now exercise my right to skip, by skipping right over the 19th century and coming down early in the 20th for my last snapshots of atmospheric ideas.

I begin with The Dynamical Theory of Gases by Sir James Jeans,[48] first published in 1904, with a second edition in 1916, and my quotations are from the fourth edition (1925). It is a classic text, and he shows quite clearly how in an isothermal atmosphere 'the heavier gases tend to sink...while the lighter ones rise to the top', because their decrease of density with height is slower. His theory is excellent and, regarded as a text-book, his work is superb. But when he ventures into the real world, he does not do so well. His table of densities in the atmos-

Darts from the north on pale electric streams,
Fringing Night's sable robe with transient beams.[39]

5. ERASMUS DARWIN

That brings me to the subject of my next dip into ideas about the atmosphere, Erasmus Darwin (1731-1802). In his classic paper[40] published in 1788, Fig 15, Darwin establishes the principle of adiabatic expansion and explains the main mode of formation of clouds. First he shows by numerous experiments - with airguns, with the high-pressure air in the waterworks at Derby, and various other exotic examples - how air cools when allowed to expand from higher pressure to lower, as for example in air being let out of a car tyre. He then applies this principle to explain what he calls the 'devaporation* of aerial moisture'.

> When large districts of air from the lower parts of the atmosphere are raised two or three miles high, they become so much expanded by the great diminution of the pressure over them,

Darwin says, that the air

> robs the vapour which it contains of its heat, whence that vapour becomes condensed and is precipitated in showers.

(Darwin's use of the verb precipitated in this sense is 75 years earlier than the first example given in the Oxford English Dictionary.) This insight on cloud formation is quite fundamental, of course, and Dalton built on it a few years later with his law of partial pressures and other ideas.[42] Darwin made several further contributions to meteorology, such as recognizing the existence and importance of what we now call cold and warm fronts.[43]

Darwin also provided a picture of the complete atmosphere. That can be found in the notes to his poem The Botanic Garden (1791), which is a review of scientific knowledge in the Earth sciences, as well as a poem which gave him the highest reputation in the literary world at the time.[44] His description of the atmosphere, which I have converted into a diagram, Fig 16, takes ideas from many predecessors[45] and adds several of his own. The result is quite a realistic three-layer model. Darwin's first stratum, with clouds and lightning, corresponds closely with what we call the troposphere, though Darwin's height of 6 km (actually he gives 4 miles) is much lower than the modern figure of about 10 km. However, his second and cloudless region does correspond closely to our stratosphere and lower meso-sphere. This region ends, he says, 'where the air is 3000 times rarer than at the surface of the Earth' and his estimate of density, which closely follows

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*Devaporation is a word coined by Darwin, meaning 'condense into droplets' - the opposite of evaporation. It would be preferable to our ambiguous modern word condense, as Knowles Middleton has remarked.[41]

pressure, winds and rainfall, using newly-designed instruments.[34] Many such weather records began to be kept - enough to allow a detailed picture of the weather in central England from 1659 to the present day.[35]

It was Edmond Halley (1656-1742) who applied Boyle's Law to the atmosphere and determined the variation of air pressure with height, in a remarkable paper in the Philosophical Transactions of the Royal Society in 1686, entitled 'A Discourse of the Rule of the Decrease of the Height of the Mercury in the Barometer, according as Places are elevated above the Surface of the Earth'.[36] Although Halley conducts his analysis with verbal argument, his procedure is equivalent to using equation (1) with T constant, in conjunction with the hydrostatic equation (2). He then deduces that the decrease of pressure with height is exponential, as in equation (4). The table he gives, Fig 13, goes up to 53 miles height, and when you compare his values with those in recent models, such as the U.S. Standard Atmosphere, 1976,[11] you find that he did very well indeed, as shown in Fig 14. Although unaware of it, Halley was assuming that the temperature remains constant as the height increases. This assumption, though incorrect, is not too far from the truth up to about 120 km height, because the average temperature in that region is only about 10% less than the sea-level temperature, as Fig 1 shows. At heights above 120 km the temperature increases greatly; consequently the pressure in the real atmosphere comes nearer to Halley's model at heights above 120 km, and eventually the two curves cross over. If the standard thermospheric temperature is taken[11] as 1000 K, it turns out that Halley's model gives the correct pressure at a height of 160 km, where the pressure is 3 nanobars.[11]

That takes us up to and above the heights of most auroral displays, and on this subject too Halley made a crucial contribution. He watched the great aurora of 1716 for several hours and wrote a long paper about it.[37] In this paper he not only gives a vivid description; he also deduces that the aurora is under the control of the Earth's magnetic field and he suggests measuring its height by triangulation. Halley also hinted that the actual 'luminous effluvia' of the aurora might be electrical in nature, and this idea became accepted during the 18th century. The 'electricians' of the 18th century were quite adept at producing glowing lights in what we would now call vacuum tubes, and the analogy with the aurora was recognized and accepted. In his treatise on the aurora[38] published in Paris in 1733, De Mairan went even further towards the modern view by suggesting that the aurora was an extension of the Sun's atmosphere. He also advocated measuring its height by triangulation, and a number of such height measurements by Bergman in the 1760s gave heights between 380 and 1300 km.[6]

So, by 1790 the aurora was generally believed to be a glowing electrical discharge in the high atmosphere. As Erasmus Darwin put it in his poem The Botanic Garden, the aurora

The atmosphere continued to be regarded as 'the triple region of the air' throughout the sixteenth century, a view that is often reflected in the imagery of the Elizabethan poets. Marlowe's Tamburlaine the Great is a good source, because Tamburlaine himself is for ever boasting about his prowess, and challenging the powers of the air, as when he treads on the defeated emperor Bajazeth:

Now clear the triple region of the air,
And let the majesty of heaven behold
Their Scourge and Terror tread on Emperors.

And he seeks to rival even the most violent natural phenomena.

As when a fiery exhalation
Wrapt in the bowels of a freezing cloud,
Fighting for passage, makes the Welkin crack,
And casts a flash of lightning to the earth ...
So shall our swords, our lances and our shot,
Fill all the air with fiery meteors.[31]

It is also worth remembering that earthquakes were regarded as largely meteorological, caused not by Earth movement but by air trying to escape from inside the Earth. A good example is provided by Shakespeare's lines:

As when the wind, imprison'd in the ground,
Struggling for passage, earth's foundation shakes,
Which with cold terror doth men's minds confound.[32]

The imagery of the Elizabethan poets can fairly be called pre-scientific, although not necessarily wrong, of course. The enduring reality of their faith in Aristotle is nicely summarized by a slightly later poet, Cowley:

Welcome, great Stagirite, and teach me now
All I was born to know.[33]

This verse serves as a fitting finale to the Aristotelian epoch, for it was published in 1656, just as new ideas were sweeping over the dreaming spires of the Aristotelian stronghold, where today the poet's name, converted into a symbol of technology, is better known than the Stagirite's.

4. THE INVISIBLE COLLEGE, THE ROYAL SOCIETY AND HALLEY

The new scientific attitude to nature typified by the 'Invisible College' at Oxford in the 1650s and then by the Royal Society in the 1660s, bore its earliest fruits in the field of atmospheric physics. Robert Boyle came to Oxford in 1654, and recruited Robert Hooke to help him in 1655. The experiments made in the late 1650s in the house on the High Street - a site now occupied by the memorial to the aerial poet Shelley - led to the formulation of what is today known as Boyle's Law, which is a restricted version of equation (1), with T and M constant.

This was one decisive step towards a better understanding of the atmosphere. Another step, equally important, was the new emphasis on measurement, of temperature,

Fig 4

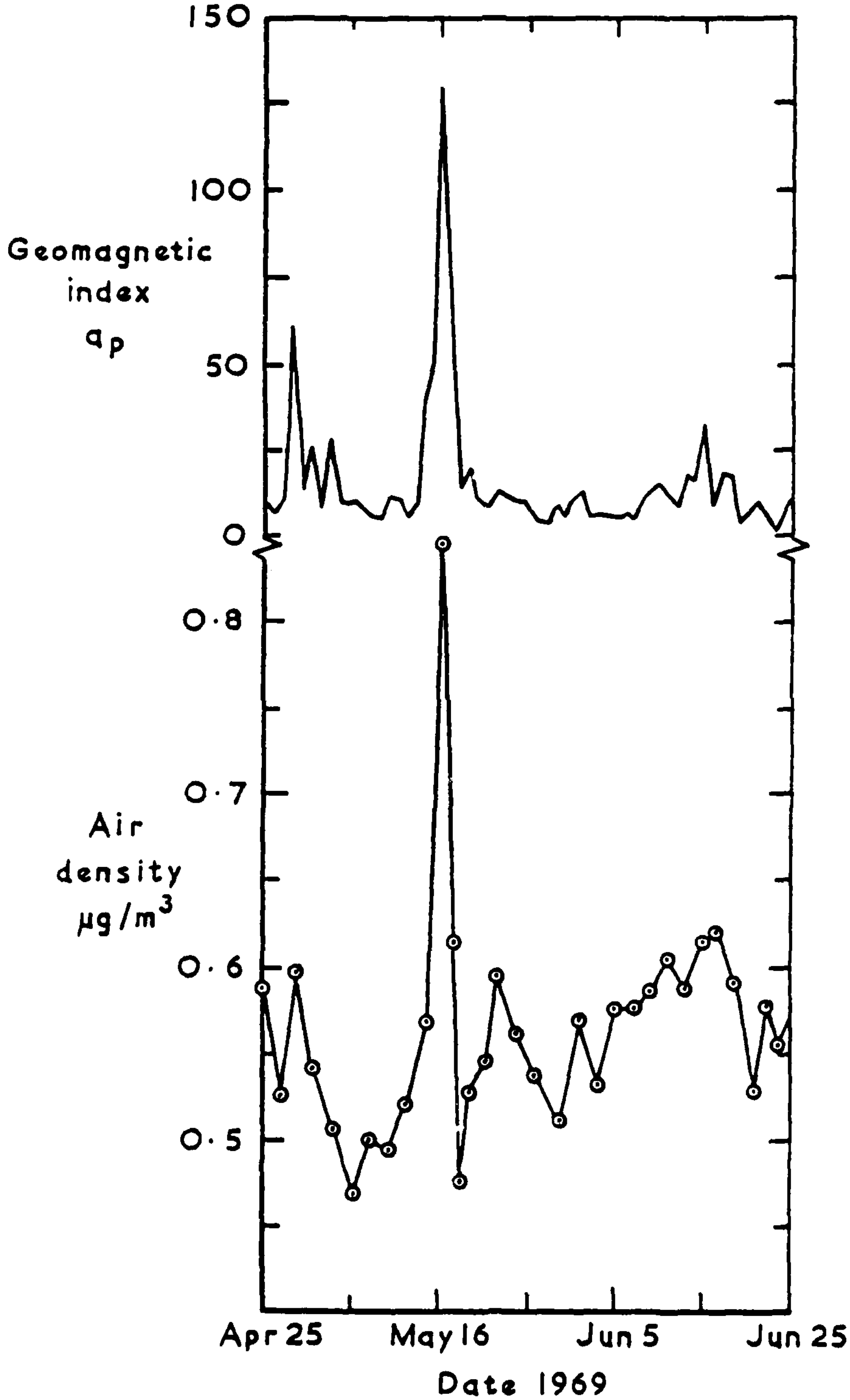


Fig 4 Increase in air density at 180 km height at the time of a magnetic storm. From Ref 12.

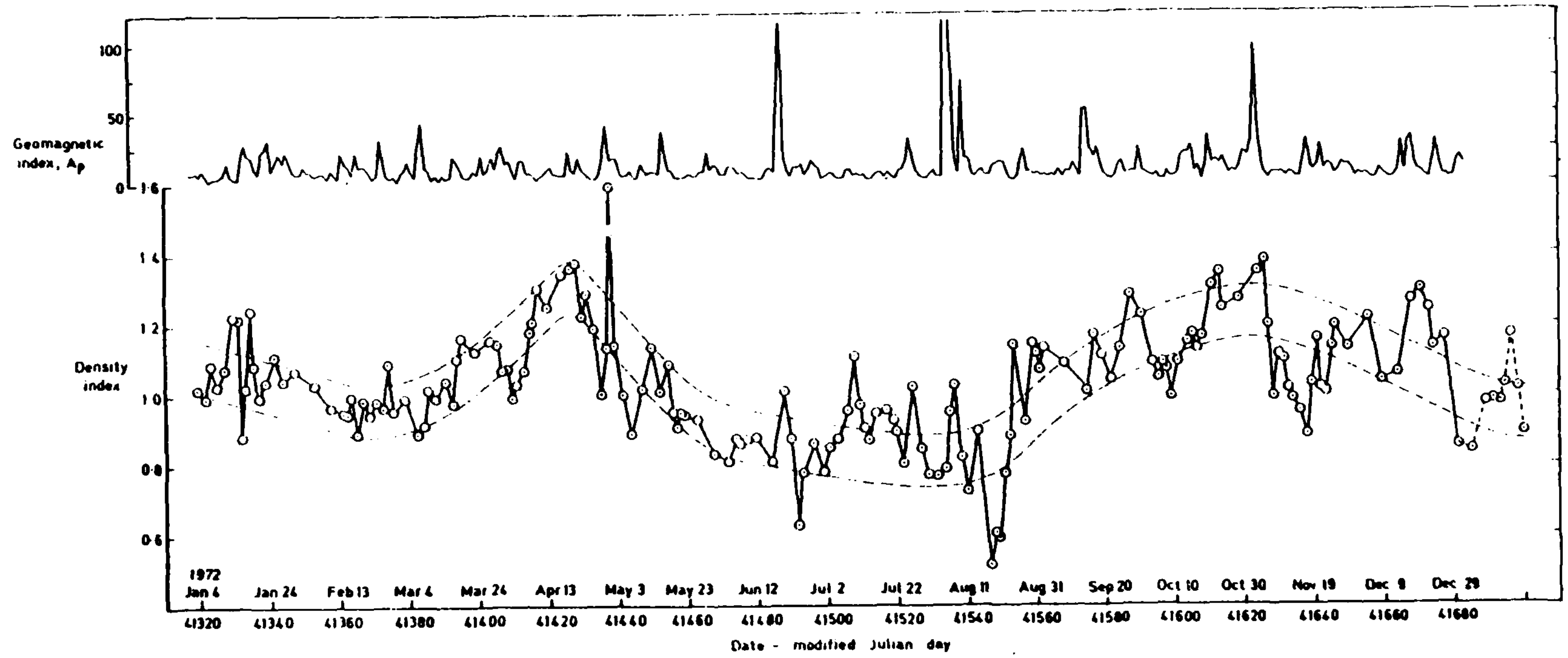
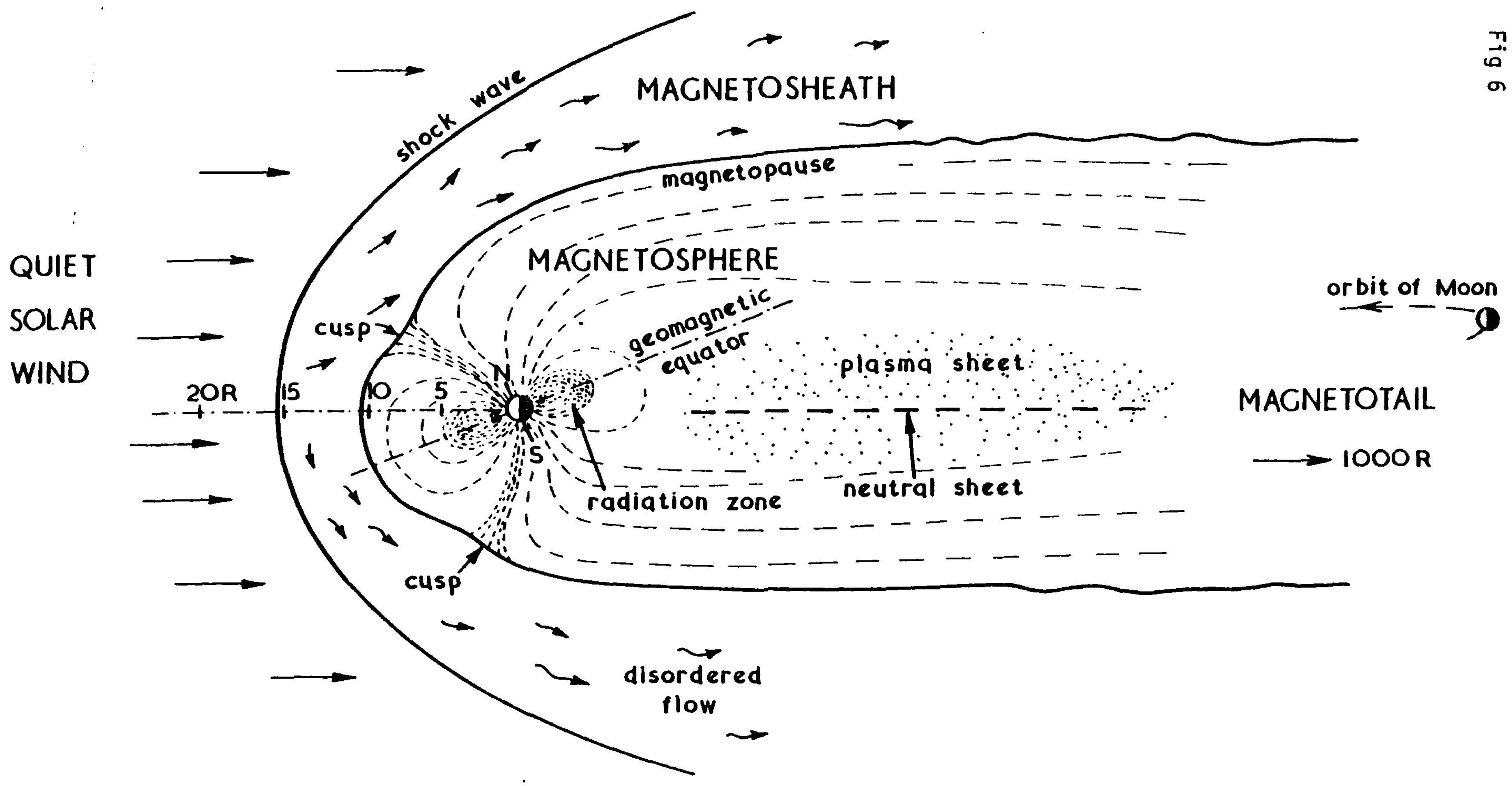


Fig 5 Variation of air density in 1972, at a height of 245 km, after removal of solar-activity and day-to-night effects, from analysis of the orbit of Cosmos 462

Fig 6



Key : N S (Earth symbol) = Earth ; — — — geomagnetic field lines ; ⟶ particle flows ;

R = Earth's radius ; (stippled) regions of enhanced particle population

Fig 6 Sketch of the magnetosphere, reproduced from Phil Trans, A278 73 (1975)

Περὶ μὲν οὖν τῶν πρώτων αἰτίων τῆς φύσεως καὶ περὶ πάσης κινήσεως φυσικῆς, ἔτι δὲ περὶ τῶν κατὰ τὴν ἄνω φορὰν διακεκοσμημένων ἄστρων καὶ περὶ τῶν στοιχείων τῶν σωματικῶν, πόσα τε καὶ ποῖα, καὶ τῆς εἰς ἄλληλα μεταβολῆς, καὶ περὶ γενέσεως καὶ φθορᾶς τῆς κοινῆς εἴρηται πρότερον. λοιπὸν δ᾽ ἐστὶ μέρος τῆς μεθόδου ταύτης ἔτι θεωρητέον, ὃ πάντες οἱ πρότεροι μετεωρολογίαν ἐκάλουν· ταῦτα δ᾽ ἐστὶν ὅσα συμβαίνει κατὰ φύσιν μέν, ἀτακτοτέραν μέντοι τῆς τοῦ πρώτου στοιχείου τῶν σωμάτων, περὶ τὸν γειτνιῶντα μάλιστα τόπον τῇ φορᾷ τῇ τῶν ἄστρων, οἷον περί τε γάλακτος καὶ κομητῶν καὶ τῶν ἐκπυρουμένων καὶ κινουμένων

Fig 7 The opening of Aristotle's Meteorologica in the Loeb edition

Fig 8

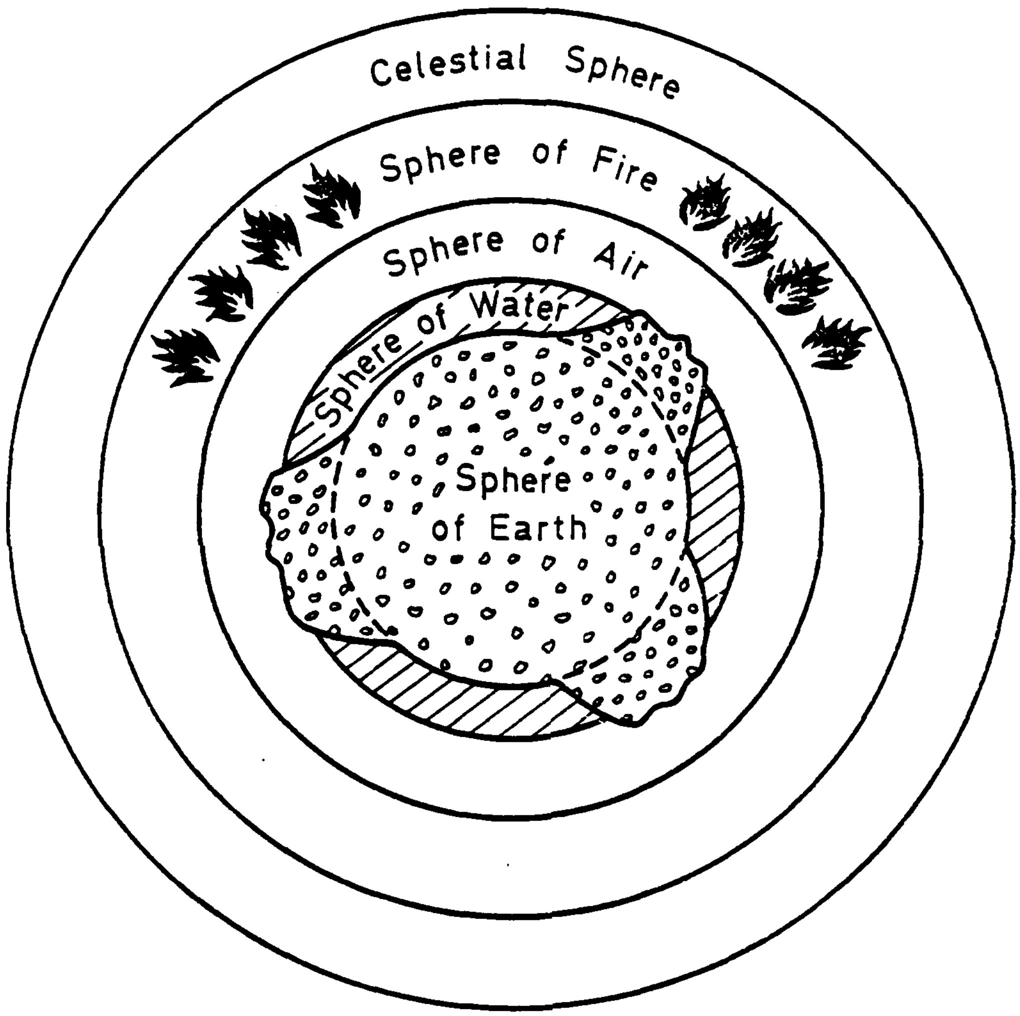


Fig 8 Aristotle's view of the Earth and its atmosphere

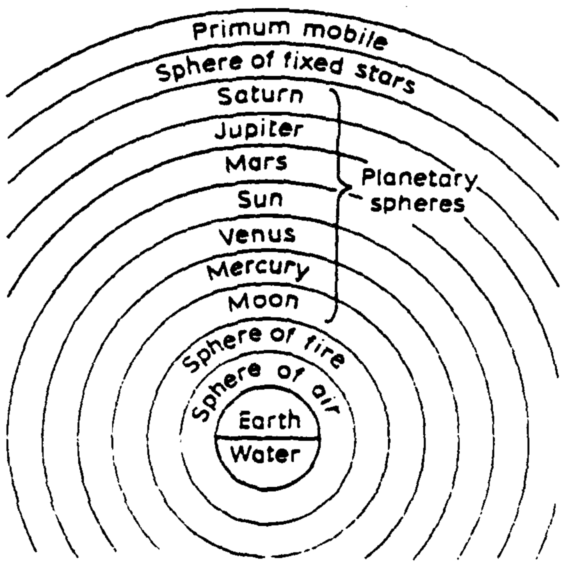


Fig 9 One version of Aristotle's model of the universe

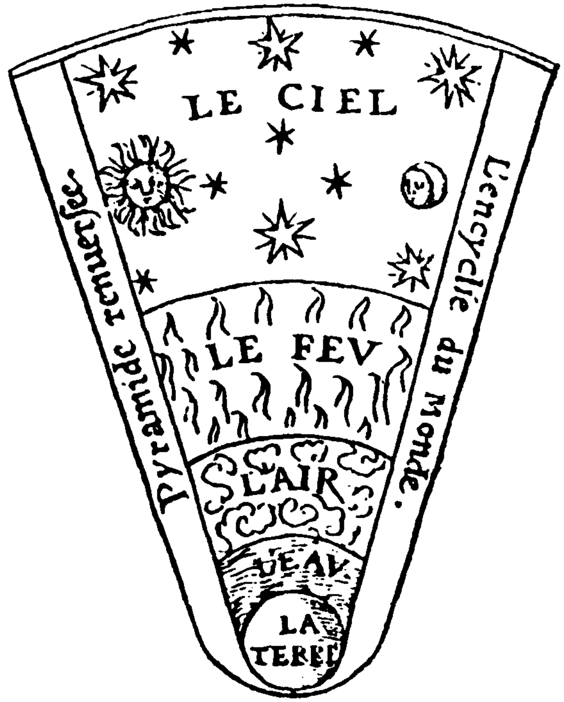


Fig 10 The spheres of Earth, Water, Air and Fire. After C. de Bouelles, Geometrie Practique (1551)

Fig 11 The threefold atmosphere. After O. Fine, Protomathesis (1532)

Fig 12

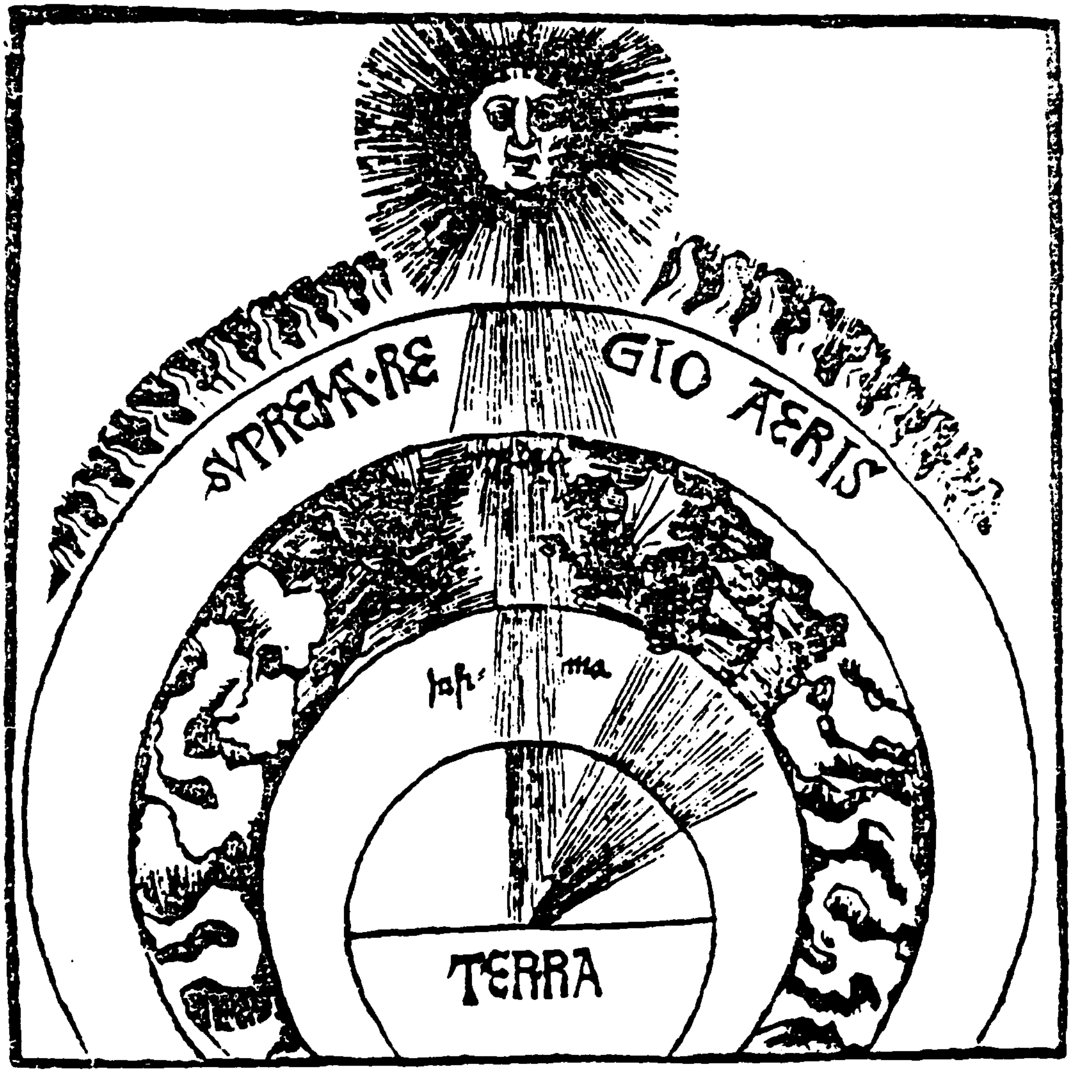


Fig 12 The Sun in command of the atmosphere. Aft G. Reisch, Margarita Philosophica Nova (1512)

From theſe Rules I derived the following Tables.

A Table ſhewing the Altitude to given Heights of the Mercury.

Inch.	*Feet.*
30	0
29	915
28	1862
27	2844
26	3863
25	4922
20	10947
15	18715
10	29662
5	48378
1	91831
0, 5	110547
0, 25	129262
0, 1	29 *mil. or* 154000
0, 01	41 *mil.* 216169
0, 001	53 *mil.* 278338

A Table ſhewing the Heights of the Mercury *at given Altitudes.*

Feet.	*Inch.*
0	30, 00
1000	28, 91
2000	27, 86
3000	26, 85
4000	25, 87
5000 *feet*	24, 93
1 *mile*	24, 67
2	20, 29
3	16, 68
4	13, 72
5	11, 28
10	4, 24
15	1, 60
20	0, ~~93~~59
25	0, 23
30	0, 08
40	0, 012

Fig 13 Halley's tables of the decrease of atmospheric pressure with height (1686), with a misprint corrected

Fig 14

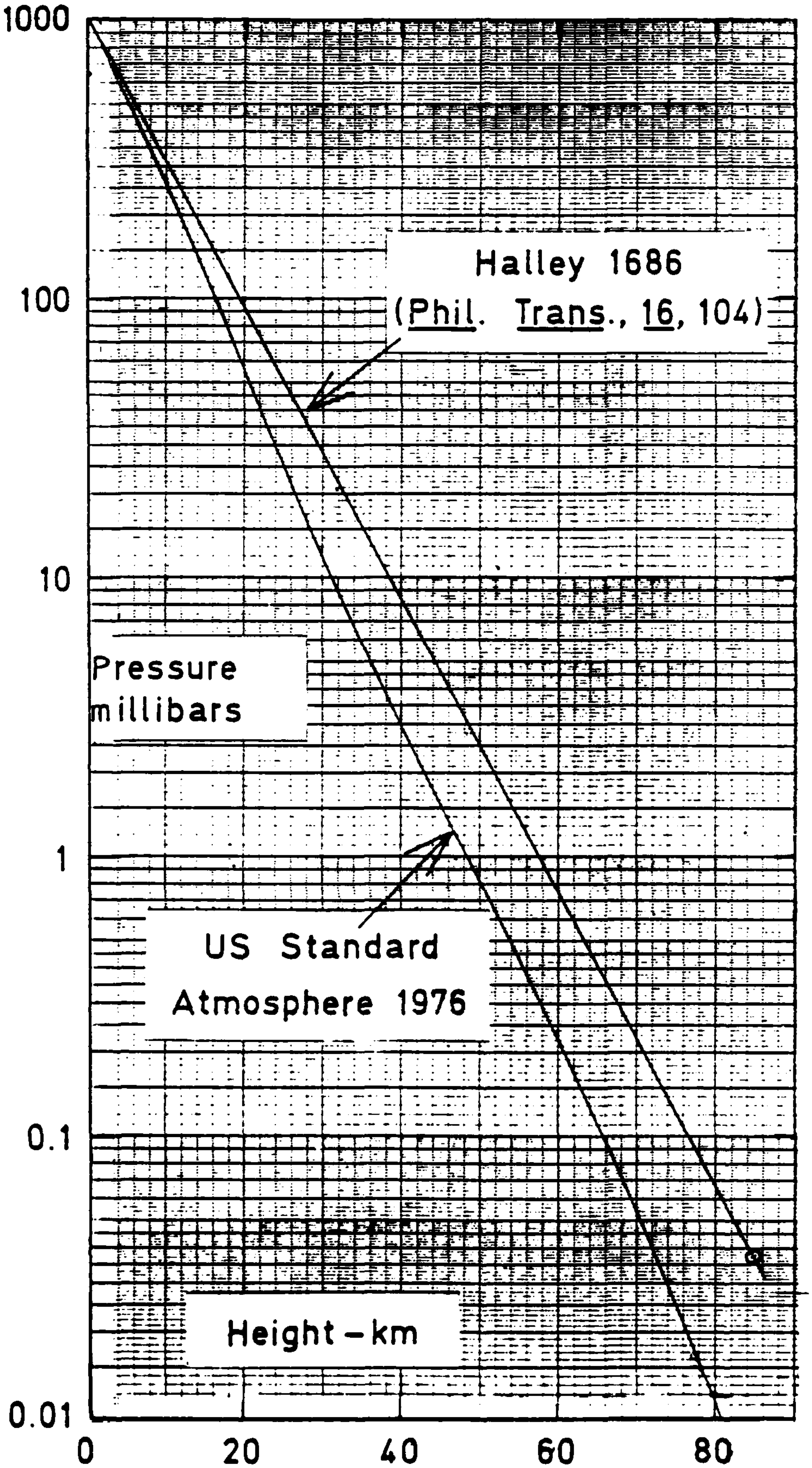


Fig 14 The decrease of atmospheric pressure with height, as given by Halley (1686) and by a modern standard

IV. **Frigorific Experiments on the mechanical expansion of Air,** *explaining the Cause of the great Degree of Cold on the Summits of high Mountains, the sudden Condensation of aerial Vapour, and of the perpetual Mutability of atmospheric Heat. By* Erasmus Darwin, *M. D. F. R. S.; communicated by the Right Honourable* Charles Greville, *F. R. S.*

Read December 13, 1787.

HAVING often revolved in my mind the great degree of cold producible by the well known experiments on evaporation; in which, by the expansion of a few drops of ether into vapour, a thermometer may be sunk much below the freezing point; and recollecting at the same time the great quantity of heat which is necessary to evaporate or convert into steam a few ounces of boiling water; I was led to suspect, that elastic fluids, when they were mechanically expanded, would attract or absorb heat from the bodies in their vicinity; and that, when they were mechanically condensed, the fluid matter of heat would be pressed out of them, and diffused among the adjacent bodies.

Fig 15   From the title page of Erasmus Darwin's paper explaining the formation of clouds by adiabatic expansion of moist rising air

Phil. Trans., 78. 43 (1788)

Fig 15

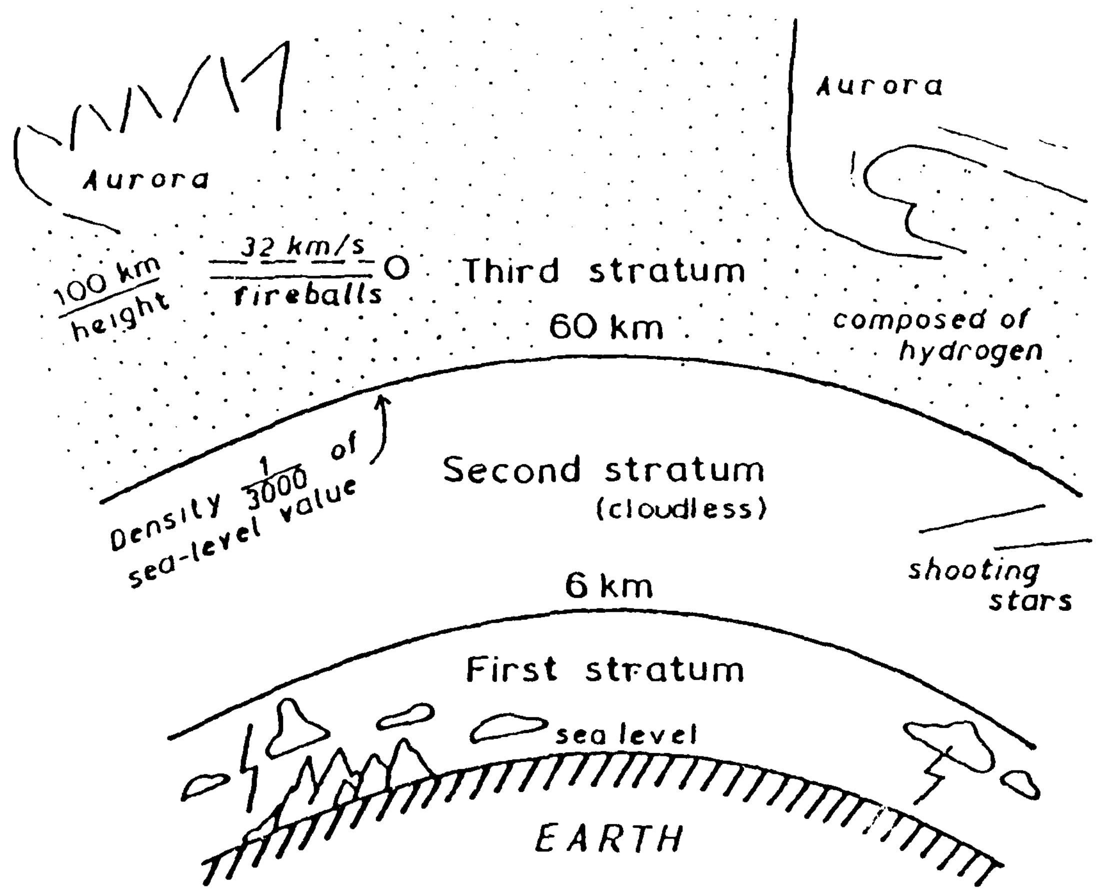


Fig 16 Erasmus Darwin's three-layer model of the atmosphere, as specified in The Botanic Garden (1791)

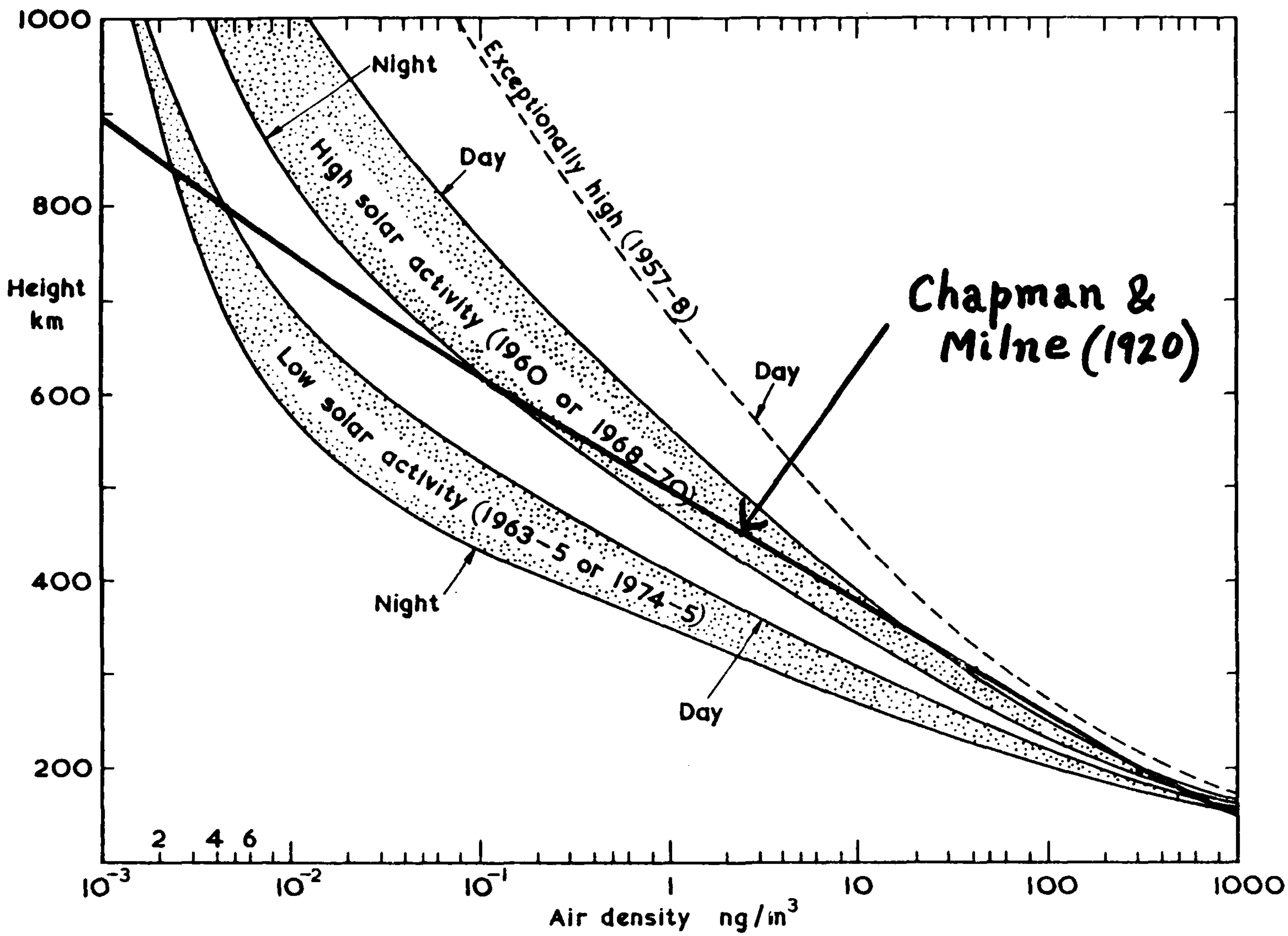


Fig 17 Variation of air density with height as given by Fig 3 and by Chapman and Milne (1920) in their 'H_T = 30 km' model

Mosaic photograph from 5 satellite passes: the straight lines mark the dividing lines between passes. Reproduced by permission of the US National Geophysical and Solar-Terrestrial Data Center.

Fig 18 Aurora and city lights, US and Canada, near midnight 14 February 1972

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17. Abstract

This is the written version of the Milne Lecture for 1984, delivered at the Mathematical Institute, University of Oxford, on 1 November 1984. It is to be published in the Quarterly Journal of the Royal Astronomical Society.

The Lecture offers a superficial survey of the modern view of the Earth's atmosphere, followed by samplings of past ideas between BC 350 and AD 1925.

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