a careful series of observations made at Washington in 1873, Prof. Asaph Hall@@1 finds that the eccentricities of the orbits of Mimas, Enceladus, Tethys, Dione, and Rhea are insensible, that of Titan is ∙0284, of Hyperion ∙1000, and that of Iapetus ⋅0278. The satel­lite Iapetus appears always to present the same face to the planet.

Concerning Uranus and Neptune there is not much to be said, as their systems are very little known ; but their masses are much larger than that of the earth, and their satellites revolve with a short periodic time. The retrograde motion and high inclination of the satellites of Uranus are very remarkable. The theory of the inclination of the orbit has been based on an assumed smallness of inclination, and it is not very easy to see to what results investi­gation might lead if the inclination were large. It must be ad­mitted, however, that the Uranian system points to the probability of the existence of a primitive planet, with retrograde rotation, or at least with a very large obliquity of equator.

It appears from this review that the other members of the solar system present some phenomena which are strikingly favourable to the tidal theory of evolution, and none which are absolutely con­demnatory. We shall show in the following section that there are reasons why the tidal friction arising in the planetary systems cannot have had so much effect as in the case of the earth and moon. That the indications which we have just noted were not more marked, but yet seemed to exist, agrees well with this conclusion.

§ 52. Influence of Tidal Friction on the Evolution of the

Solar System.

According to the nebular hypothesis, the planets and the satellites are portions detached from contracting nebulous masses. In the following discussion that hypothesis will be accepted in its main outline, and we shall examine what modifications are necessitated by the influence of tidal friction. It may be shown that the reaction of the tides raised in the sun by the planets must have had a very small influence in changing the dimensions of the planetary orbits round the sun. From a consideration of numerical data with regard to the solar system and the planetary subsystems, it appears improbable that the planetary orbits have been sensibly enlarged by tidal friction since the origin of the several planets. But it is possible that some very small part of the eccentricities of the planetary orbits is due to this cause. From arguments similar to those advanced with regard to the solar system as a whole, it appears unlikely that the satellites of Mars, Jupiter, and Saturn originated very much nearer the present surfaces of the planets than we now observe them. But, the data being insufficient, we cannot feel sure that the alteration in the dimensions of the orbits of these satellites has not been considerable. It remains, however, nearly certain that they cannot have first originated almost in con­tact with the present surfaces of the planets, in the same way as in the preceding sketch (§ 50) has been shown to be probable with regard to the moon and earth. Numerical data concerning the distribution of moment of momentum in the several planetary sub-systems exhibit so striking a difference between the terres­trial system and those of the other planets that we should from this alone have grounds for believing that the modes of evolution have been considerably different. The difference appears to lie in the genesis of the moon close to the present surface of the planet, and we shall see below that solar tidal friction may be as­signed as a reason to explain how it has happened that the terres­trial planet had contracted to nearly its present dimensions before the genesis of a satellite, but that this was not the case with the exterior planets. The efficiency of solar tidal friction is very much greater in its action on the nearer planets than on the further ones. The time, however, during which solar tidal friction has been operating on the external planets is probably much longer than the period of its efficiency for the interior ones, and a series of numbers proportional to the total amount of rotation destroyed in the several planets would present a far less rapid decrease as we recede from the sun than numbers simply expressive of the efficiency of tidal friction at the several planets. Nevertheless it must be admitted that the effect produced by solar tidal friction on Jupiter and Saturn has not been nearly so great as on the interior planets. And, as already stated, it is very improbable that so large an amount of momentum should have been destroyed as to materially affect the orbits of the planets round the sun.

We will now examine how the differences of distance from the sun would be likely to affect the histories of the several planetary masses. According to the nebular hypothesis, a planetary nebula contracts, and rotates quicker as it contracts. The rapidity of the revolution causes it to become unstable, or perhaps an equatorial belt gradually detaches itself ; it is immaterial which of these two really takes place. In either case the separation of that part of the mass which before the change had the greatest angular momentum permits the central portion to resume a planetary shape. The contraction and the increase of rotation proceed continually until another portion is detached, and so on. There thus recur at inter­vals a series of epochs of instability or of abnormal change. Now

tidal friction must diminish the rate of increase of rotation due to contraction, and therefore if tidal friction and contraction are at work together the epochs of instability must recur more rarely than if contraction alone acted. If the tidal retardation is suffi­ciently great, the increase of rotation due to contraction will be so far counteracted as never to permit an epoch of instability to occur. Since the rate of retardation due to solar tidal friction decreases rapidly as we recede from the sun, these considerations accord with what we observe in the solar system. For Mercury and Venus have no satellites, and there is a progressive increase in the number of satellites as we recede from the sun. Moreover, the number of satellites is not directly connected with the mass of the planet, for Venus has nearly the same mass as the earth and has no satellite, and the earth has relatively by far the largest satellite of the whole system. Whether this be the true cause of the observed distribu­tion of satellites amongst the planets or not, it is remarkable that the same cause also affords an explanation, as we shall now show, of that difference between the earth with the moon and the other planets with their satellites which has caused tidal friction to be the principal agent of change with the former but not with the latter. In the case of the contracting terrestrial mass we may suppose that there was for a long time nearly a balance between the retardation due to solar tidal friction and the acceleration due to contraction, and that it was not until the planetary mass had contracted to nearly its present dimensions that an epoch of instability could occur. It may also be noted that if there be two equal planetary masses which generate satellites, but under very different conditions as to the degree of condensation of the masses, the two satellites will be likely to differ in mass ; we cannot of course tell which of the two planets would generate the larger satellite. Thus, if the genesis of the moon was deferred until a late epoch in the history of the terrestrial mass, the mass of the moon relatively to the earth would be likely to differ from the mass of other satellites relatively to their planets. If the contraction of the planetary mass be almost completed before the genesis of the satellite, tidal friction, due jointly to the satellite and to the sun, will thereafter be the great cause of change in the system ; and thus the hypothesis that it is the sole cause of change will give an approximately accurate explanation of the motion of the planet and satellite at any subsequent time. We have already seen that the theory that tidal friction has been the ruling power in the evolution of the earth and moon coordinates the present motions of the two bodies and carries us back to an initial state when the moon first had a separate existence as a satellite ; and the initial configuration of the two bodies is such that we are led to believe that the moon is a portion of the primitive earth detached by rapid rotation or other causes. There seems to be some reason to suppose that the earliest form in which the moon had a separate existence was as a ring or chain of meteorites ; but this condition precedes that to which the dynamical investigation leads back.

Let us now turn to the other planetary sub-systems. The satellites of the larger planets revolve with short periodic times ; this admits of a simple explanation, for the smallness of their masses would have prevented tidal friction from being a very efficient cause of change in the dimensions of their orbits, and the largeness of the planet’s masses would have caused them to proceed slowly in their evolution. If the planets be formed from chains of meteorites or of nebulous matter, their rotation has arisen from the excess of orbital momentum of the exterior over that of the interior matter. As we have no means of knowing how broad the chain may have been in any case, nor how much it may have closed in on the sun in course of concentration, we are unable to compute the primitive angular momentum of a planet. A rigorous method of comparison of the primitive rotations of the several planets is thus wanting. If, however, the planets were formed under similar conditions, then we should expect to find the exterior planets now rotating more rapidly than the interior ones. On making allowance for the differ­ent degrees of concentration of the planets, this is the case. That the inner satellite of Mars revolves with a period of less than a third of the planet’s rotation is perhaps the most remarkable fact in the solar system. The theory of tidal friction explains this perfectly ; and this will be the ultimate fate of all satellites, be­cause the solar tidal friction retards the planetary rotation without directly affecting the satellite’s orbital motion. Numerical com­parison shows that the efficiency of solar tidal friction in retarding the terrestrial and martian rotations is of about the same degree of importance, notwithstanding the much greater distance of the planet Mars. In the above discussion it will have been apparent that the earth and moon do actually differ from the other planets to such an extent as to permit tidal friction to have been the most important factor in their history.

By an examination of the probable effects of solar tidal friction on a contracting planetary mass, we have been led to assign a cause for the observed distribution of satellites in the solar system, and this again has itself afforded an explanation of how it happened that the moon so originated that the tidal friction of the lunar tides in the earth should have been able to exercise so large an

@@@1 bee *Brit. Assoc. Report,* 1886, p. 543.