where, waiting for noon, the moment of which I ascertain by observing the sun, I find that my time-piece indicates only 58′ 15″ after X.; so that then it is not yet noon at Berlin, and the difference of time is 1 hour 1′ 45″, from which I conclude, that the place at which I have arrived is to the eastward of Berlin; and as one hour gives 15 degrees, one minute of time 15′, and 45 seconds of time 11′ 15″, the difference of the meridians will therefore be 15° 26′ 15″. I find, then, that I am at a place to the eastward of Berlin, whose longitude is greater than that of Berlin by 15° 26′ 15″; now the longitude of that city being nearly 31° 7′ 15″, the longitude of the place where I am must be 46° 33′ 30″. Thus I have discovered under what meridian I now am; but I am still uncertain as to the point of the meridian. In order to ascertain this I have recourse to astronomical observations, and find the height of the pole to be precisely 41°. Knowing likewise that I am still in the northern hemisphere, as I have not passed the equator, I discover that I actually am at a place whose latitude is 41° north, and longitude 46° 33′ 30″. I take therefore my globe or maps, and trace the meridian whose longitude is 46° 33′ 30″; I look for the place whose latitude is 41°, and at the point of intersection I find I have got to the city of Constantinople, without having occasion to apply for information to any person whatever.

Thus, at whatever place of the globe I may arrive, possessed of a time-piece so exact, I am able to ascertain the longitude of it; and then an observation of the height of the pole will show me its latitude. All that remains, therefore, is to take the terrestrial globe, or a good map, and it will be easy for me to ascertain where I am, however unknown to me the country may in other respects be.

It is much to be regretted, that artists of the greatest ability have hitherto been unsuccessful in the construction of time-pieces, such as I have described, and such as the case requires. We meet with a great many very good pendulum machines, but they go regularly only when fixed in undisturbed situations; the slightest concussion is apt to derange their motion; they are therefore totally useless in long sea voyages. It is obvious that the pendulum, which regulates the motion, is incapable of resisting the shocks to which it is exposed in navigation. About ten years ago, however, an English artist pretended that he had constructed a time-piece proof against the motion of a ship at sea, and that after having tried it a long time together in a carriage on the road, it was impossible to perceive the slightest derangement; on which the inventor claimed and received part of the parliamentary reward proposed for the discovery of the longitude, and the rest was to be paid after it had been put to the proof of a long voyage. But since that time we have heard no more of it; from which it is to be presumed that this attempt too has failed, like many others which had the same object in view.*

19th September 1761.

LETTER L.—ECLIPSES OF THE MOON, A THIRD METHOD OF FINDING THE LONGITUDE.

FROM want of the exquisite time-piece, of which I have endeavoured to give you an idea, the eclipses of the moon have hitherto been considered as the

* The success of these attempts has been very great. The chronometers of Harrison, Earnshaw, Arnold, &c. in England, and those of M. Breguet in Paris, and of M. Jurgensen at Copenhagen, enable the navigator to determine his longitude at sea with an extraordinary degree of accuracy. —ED.

most certain method of discovering the longitude; but these phenomena present themselves so rarely, that we have it not in our power to employ them so often as occasion requires.

You know that the moon is eclipsed when it passes into the shadow of the earth: it is possible, then, to observe the moment when the moon begins to enter into the shade, and when she has emerged; the one is denominated the beginning of the eclipse, and the other its end; and when both are observed, the mean time betwixt them is denominated the middle of the eclipse. The moon is sometimes wholly immerged in the shadow of the earth, and remains for some time invisible; this we call a total eclipse, during which we may remark the moment when the moon entirely disappears, and that when she begins to emerge; the former is called the beginning of total darkness, and the latter the end of it. But when a part only of the moon is obscured, we call it a partial eclipse; and we can remark only the moment of its beginning and ending. You know likewise that eclipses of the moon can happen only at the full, and that but rarely.

When, therefore, an eclipse of the moon is observed at two different places situated under different meridians, the beginning of the eclipse will be clearly seen at both, and at the same instant; but the time-pieces at these different places will by no means indicate the same hour, or any other division of time exactly the same: I mean well regulated time-pieces, each of which points precisely to XII. when it is noon at that place. If these places are situated under the same meridian, their time-pieces will no doubt indicate the same time at the beginning and at the end of the eclipse. But if these two meridians are 15 degrees distant from each other, that is, if the difference of their longitude be 15°, the time-

pieces must differ a complete hour from the beginning to the end of the eclipse; the time-piece of the place situated to the eastward will indicate one hour more than the other: the difference of 30° in longitude will occasion that of two hours in the time indicated by well regulated clocks or watches; and so on, according to the following table:

DIFFERENCE OF LONGITUDE.		DIFFERENCE OF LONGITUDE.	
Of Degrees.	Of Time.	Of Degrees.	Of Time.
15°	1 Hour.	105°	7 Hours.
30	2	120	8
45	3	135	9
60	4	150	10
75	5	165	11
90	6	180	12

If, therefore, the difference of the longitude were 150°, the time-pieces would differ ten hours from the beginning to the end of the eclipse.

Thus, when the same eclipse is observed at two different places, and the moment of its commencement is exactly marked on the time-pieces at each, it will be easy to calculate, from the difference of the time indicated, the difference of longitude between the two places. Now, that where the time is more advanced, must be situated more toward the east, and consequently its longitude greater, as longitude is reckoned from west to east.

By such means, accordingly, the longitude of the principal places on the globe have been determined, and geographical charts are constructed conformably to these determinations. But it is always necessary to compare the observations made in a place, the longitude of which was not already known, with those which had been made in a known place, and to wait the result of that comparison. Were I to arrive, then, after a long voyage, at an unknown place, and an opportunity presented itself of there observing an eclipse of the moon, this would, in the first instance, afford me no assistance toward the discovery of the longitude of that place; I could not, till after my return, compare my observation with another made in a known place, and thus I should learn too late where I was at that time. The grand point in request is, How am I at the moment to acquire the necessary information, that I may take my measures accordingly?

Now, the motion of the moon being so exactly known, it is possible to attain this satisfaction; for we are thereby enabled not only to calculate beforehand all future eclipses, but to ascertain the moment of the beginning and end, according to the time-pieces of a given place. You know that our Berlin almanacks always indicate the beginning and the end of every eclipse visible at that city. In the view, then, of undertaking a long voyage, I can furnish myself with a Berlin almanack; and if an opportunity presents itself of observing an eclipse of the moon at an unknown place, I must mark exactly the time of it, by a time-piece accurately regulated by the sun at noon, and compare the moments of the beginning and end of the eclipse with those indicated in the almanack, in order to ascertain the difference between the meridian of Berlin, and that which passes through the place where I am.

But beside the rarity of eclipses of the moon, this method is subject to a farther inconvenience; we are not always able to distinguish with sufficient accuracy the moment of the beginning and end of the eclipse, which comes on so imperceptibly, that a mistake of several seconds may very easily be committed. But as the mistake will be nearly the

same at the end as at the beginning, we calculate the middle point of time between the two moments observed, which will be that of the eclipse; and we afterwards compare this with that which is indicated by the almanack for Berlin, or for any other known place.

If the almanack for next year should not be published when I set out on my voyage, or supposing it to last more years than one, there are books containing the eclipses calculated for several years to come.

22d September 1761.

Letter LI.—Observation of the Eclipses of the Satellites of Jupiter, a Fourth Method of Finding the Longitude.

Eclipses of the sun may likewise assist in ascertaining the longitude, but in a way that requires more profound research, because the sun is not immediately obscured; it is only the interposition of the body of the moon which obstructs the transmission of his rays to us, as when we employ a parasol to shelter us from them, which does not prevent others from beholding all their lustre. For the moon conceals the sun only from part of the inhabitants of the earth; and an eclipse of the sun may be clearly visible at Berlin, while at Paris there is no interception of his light.

But the moon is really eclipsed by the shadow of the earth; her own light is diminished or extinguished by it: hence the eclipses of the moon are seen in the same manner, wherever she is above the horizon at the time of the eclipse.

It cannot have escaped your penetration, that if there were other heavenly bodies which from time to time underwent any real obscuration, they might be employed with similar success as the eclipses of the moon in ascertaining the longitude. The satellites of Jupiter, which pass so frequently into the shadow of their planet, that almost every night one or other of them is eclipsed, may be ranked in the number of these, and furnish us with another excellent method of determining the longitude. Astronomers accordingly employ it with great success.

You know that Jupiter has four satellites, which make their revolutions round him, each in his own orbit, as represented in the annexed figure (PLATE IV. *Fig.* 1.), by circles described round Jupiter. I have likewise represented the sun in this figure, in order to exhibit the shadow AOB behind the body of Jupiter. You see the first of these satellites, marked 1, on the point of entering into the shadow; the second, marked 2, has just left it; the third, 3, is still at a great distance, but approaching to it; and the fourth, 4, has left it a considerable time ago.

As soon as one of these satellites passes into the shadow, it becomes invisible, and that suddenly; so that at whatever place of the globe you may happen to be, the satellite which was before distinctly visible disappears in an instant. This entrance of a satellite into the shadow of Jupiter is denominated *Immersion*, and its departure from the shadow *Emersion*; when the satellite, which had for some time been invisible, suddenly re-appears.

The immersions and emersions are equally adapted to the determination of the longitude, as they take place at a decided instant; so that when such a phenomenon is observed at several places of the globe, you must find, in the time indicated by the time-pieces of each, the difference which exactly corresponds to the difference of the distance of their meridians. It is the same thing as if we observed the beginning or the end of an eclipse of the moon; and

the case is then involved in no difficulty. For some time past, we have been able to calculate these eclipses of the satellites of Jupiter, that is, their immersions and emersions; and we have only to compare the time observed, with the time calculated for a given place, say Berlin, in order to conclude, at once, the distance of its meridian from that of our capital.

This method is accordingly practised universally in travelling by land; but the means have not yet been discovered of profiting by it at sea, where, however, it is of still greater importance for a man to know with certainty where he is. Were the satellites of Jupiter as visible to the naked eye as the moon is, this method would be attended with no difficulty, even at sea; but the observation cannot be made without a telescope of at least four or five feet in length—a circumstance which presents an insurmountable obstacle.

You well know that it requires some address to manage, even at land, a telescope of any length, to direct it toward the object which you wish to contemplate, and to keep it so steady as not to lose the object; you will easily comprehend, then, that a ship at sea, being in a continual agitation, it must be almost impossible to catch Jupiter himself; and if you could find him, you would lose him again in a moment. Now, in order to make an accurate observation of the immersion or emersion of one of the satellites of Jupiter, it is absolutely necessary that you should have it in your power to look at him steadily for some time together; and this being impossible at sea, we are to all appearance constrained to abandon this method of determining the longitude.

This inconvenience, however, may be remedied two ways; the one by the construction of telescopes six inches long, or less still, capable of discovering clearly the satellites of Jupiter; and there can be no doubt that these would be more manageable than such as are four or five feet in length. Artists are actually employing themselves with success in bringing telescopes of this sort to perfection; but it has not yet been proved whether or not it will require as much address to point them to the object, as those which are longer.

The other way would be to contrive a chair, to be used on ship-board, which should remain fixed and motionless, so as not to be affected by the agitation of the vessel. It does not seem impossible that a dexterous mode of balancing might effect this. In fact, it is not long since we read in the public prints, that an Englishman pretended that he had constructed such a chair, and therefore claimed the prize proposed for the discovery of the longitude.* His claim was well founded, if he indeed constructed the machine, as it would be possible, by means of it, to observe at sea the immersions and emersions of the satellites of Jupiter, which are undoubtedly very much adapted to the making of this discovery; but for some time past no farther mention has been made of it. From the whole, you must have perceived how many difficulties attach themselves to the discovery of the longitude.

26th September 1761.

Letter LII.—The Motion of the Moon, a Fifth Method.

The heavens furnish us with one resource more for discovering the longitude without the assistance of telescopes, in which astronomers seem to place

* The invention here alluded to was Irwin's Marine Chair, which was tried at sea, but it was not found to answer the purpose of the inventor.—Ed.

the greatest confidence. It is the moon, not only when eclipsed, but at all times, provided she be visible; an unspeakable advantage, considering that eclipses are so rare, and that the immersions and emersions of the satellites of Jupiter are of such difficult observation; there being a considerable time every year during which the planet Jupiter is not visible to us, whereas the moon is almost constantly in view.

You must undoubtedly have already remarked, that the moon rises every day almost three quarters of an hour later than the preceding, not being attached to one fixed place relatively to the stars, which always preserve the same situation with respect to each other, though they have the appearance of being carried round by the heavens, to accomplish every day their revolution about the earth. I speak here according to appearances; for it is the earth which revolves every day round its axis, while the heavens and the fixed stars remain at rest; while the sun and planets are continually changing their place relatively to these. The moon has likewise a motion abundantly rapid from one day to another, with relation to the fixed stars.

If you were to see the moon to-day near a certain fixed star, it will appear to-morrow at the same hour at a considerable distance from it toward the east; and the distance sometimes exceeds even 15 degrees. The velocity of her motion is not always the same, yet we are able to determine it very exactly for every day; by which means we can calculate before-hand her true place in the heavens for every hour of the day, and for any known meridian, say that of Berlin, or Paris.

Suppose, then, that after a long voyage I find myself at sea, in a place altogether unknown, what use can I make of the moon, in order to discover the longitude of the place where I am? There is no difficulty with respect to the latitude, even at sea, where there are means abundantly certain for ascertaining the height of the pole, to which the latitude is always equal. My whole attention, then, will be directed to the moon; I will compare her with the fixed stars which are nearest, and thence calculate her true place relatively to them. You know there are celestial globes on which all the fixed stars are arranged, and that celestial charts are likewise constructed, similar to geographical maps, on which are represented the fixed stars which appear in a certain quarter of the heavens. On taking, then, a celestial chart on which the fixed stars to which the moon is near are marked, it will be an easy matter to determine the true place where the moon at that time is; and my watch, which I have taken care to regulate there, from an observation of the moment of noon, will indicate to me the time of my lunar observation. Then, from my knowledge of the moon's motion, I calculate for Berlin, at what hour she must appear in the same place where I have seen her. If the time observed exactly correspond with the time of Berlin, it will be a demonstration that the place where I am is precisely under the meridian of Berlin, and that consequently the longitude is the same. But if the time of my observation is not that of Berlin, the difference will give that which is between the meridians; and reckoning 15 degrees for every hour of time, I compute how much the longitude of the place I am at is greater or less than that of Berlin: the place where time is more advanced has always the greater longitude.

This is an abstract of the manner of determining longitude by simple observations of the moon. I remark, that the happiest moments for successfully performing this operation, and for accurately determining the moon's place, are, when a fixed star happens to be concealed behind her body; this is called *Occultation*, and there are two instances favourable to observation, that when the moon in her motion completely covers the star, and that when the star re-appears. Astronomers are particularly attentive to catch these instants of occultation, in order to calculate from them the moon's true place.

I foresee, however, an objection you will probably make respecting the time-piece with which I suppose our navigator provided, after having maintained the impossibility of constructing one that shall be proof against every agitation of a ship at sea. But this impossibility respects only such time-pieces as are expected to preserve a regular motion for a long time together, without the necessity of frequent adjustment; for as to the observations in question, a common watch is quite sufficient, provided it go regularly for some hours, after having been carefully adjusted to the noon of the place where we are; supposing a doubt to arise, whether we could calculate from it the succeeding evening or night, at the time we observe the moon, the stars likewise will afford the means of a new and accurate adjustment. For as the situation of the sun with relation to the fixed stars is perfectly known for any time whatever, the simple observation of any one star is sufficient to determine the place where the sun must then be; from which we are enabled to calculate the hour that a well regulated time-piece ought to indicate. Thus, at the very instant of making an observation by the moon, we are enabled likewise to regulate our time-piece by the stars; and every time-piece is supposed to go regularly for so short a space.

29th September 1761.

LETTER LIII.—ADVANTAGES OF THIS LAST METHOD; ITS DEGREE OF PRECISION.

THIS last method of finding the longitude, founded on lunar observations, seems to merit the preference, as the others are subjected to too many difficulties, or the opportunities of employing them occur too seldom to be useful. And you must be abundantly sensible, that success depends entirely on the degree of precision attained in forming the calculation, and that the errors which may be committed would lead to conclusions on which we could place no dependence. It is of importance, therefore, to explain what degree of precision we may reasonably hope to attain in reducing this method to practice, founded on the considerable change which the moon undergoes from one day to another in her position. It may be affirmed, that if the moon's motion were more rapid, it would be more adapted to the discovery of the longitude, and would procure for us a higher degree of precision. But if, on the contrary, it were much slower, so that we could scarcely discern any change of her position from day to day, we could derive very little, if any, assistance from her toward the discovery of the longitude.

Let us suppose, then, that the moon changes her place among the fixed stars a space of 12 degrees in 24 hours; she will, in that case, change it one degree in two hours, and half a degree, or 30 minutes in an hour: if we were to commit a mistake in observing the moon's place, of 30 minutes, it would be the same thing as if we observed the moon an hour earlier or later, and we should commit a mistake of one hour in the conclusion respecting the difference of the meridians. Now, one hour's difference in the meridians corresponds to 15 degrees in their longitude; consequently, we should be mistaken 15 degrees in the longitude itself of the place we look for; which would undoubtedly be an error so enormous, that it were almost as well to know nothing about it; and a simple computation of the distance and the direction, however uncertain, could not possibly lead to a mistake so very gross. But a man must have gone to work in a very slovenly manner, to commit a mistake of 30 minutes respecting the moon's place; and the instruments which he employed must have been very bad, a thing not to be supposed.

Nevertheless, however excellent the instruments may be, and whatever degree of attention may have been bestowed, it is impossible to keep clear of all error; and he must have acquitted himself very well indeed, who has not committed the mistake of one minute in determining the moon's place. Now, as it changes half a degree, or 30 minutes, in one hour, it will change one minute of distance in two minutes of time. When, therefore, the mistake of the moon's place amounts to no more than one minute, the mistake in the difference of meridians will amount to two minutes of time. And one hour, or 60 minutes, being equivalent to 15 degrees of longitude, there will result from it an error of half a degree in the longitude; and this point of precision might be sufficient for every purpose, were it but attainable.

I have hitherto supposed our knowledge of the moon's motion to be so perfect, that, for a known meridian, we could determine the moon's true place for every moment without an error; but we are still very far short of that point of perfection. Within these twenty years, the error in this calculation was more than six minutes; and it is but lately that the ingenious *Professor Mayer* of Gottingen, pursuing the track I had pointed out to him, has succeeded so far as to reduce this error to less than a minute. It may very easily happen, then, that in the calculation likewise, the error of one minute may be committed; which, added to that of a minute committed in the observation of the moon's place, will double that which results from it respecting the longitude of the place where we are; and, consequently, it may possibly amount to a whole degree: it is proper farther to remark, that if the moon in 24 hours should change her relative situation more than 12 degrees, the error in the longitude would be less considerable. The means may perhaps be discovered of diminishing still farther the errors into which we are liable to fall, in the observation and in the calculation; and then we should be able to ascertain the longitude to a degree, or less. Nay, we ought not to despair of attaining a still higher degree of precision. We have only to make several observations, which can be easily done by remaining several days together at the same place. It is not to be apprehended, in that case, that all the conclusions should be equally defective; some will give the longitude sought too great, others too small, and by striking a medium between all the results, we may rest assured that this longitude will not be one degree removed from the truth.

The English nation, generously disposed to engage genius and ability in this important research, has proposed three prizes for ascertaining the longitude, one of L. 10,000, one of L. 15,000, and one of L. 20,000. The first of these is to be bestowed on the person who shall determine the longitude to a degree, or about it, so as to give perfect assurance that the error shall not exceed one degree at most. The second is to be given to him who shall discover a method still more exact, so that the error shall never exceed two-thirds of a degree, or 40 minutes. The highest prize is destined to the man who shall

ascertain the longitude so exactly that the error shall never exceed half a degree, or 30 minutes; and a higher degree of precision is hardly to be expected. No one of these prizes has hitherto been allotted: I do not take into the account the gratification bestowed on the artist who pretended to it from his construction of perfect time-pieces. *Mr. Mayer* is at this moment claiming the highest, and I think he is entitled to it.*

3*d October* 1761.

LETTER LIV.—ON THE MARINER'S COMPASS, AND THE PROPERTIES OF THE MAGNETIC NEEDLE.

You are by this time sufficiently informed respecting the discovery of the Longitude: I have had the pleasure of explaining the various methods which have been employed for the determination of it.

The first, and most natural, is carefully to observe the quantity of space which we have gone over, and the direction in which we moved; but the currents and tempests to which sea voyages are exposed, render this method impracticable.

The second requires the construction of a timepiece so perfect as to go always uniformly, notwithstanding the agitation of a ship at sea; which no artist has hitherto been able to accomplish.

The third is founded on the observation of the eclipses of the moon, which would completely answer every purpose, were not opportunities of employing it too rare, and least in our power when the necessity may be most urgent.

* The widow of Professor Mayer received from the British Parliament a reward of L. 3000 Sterling; and Euler himself received L. 300 for furnishing the theorems on which Mayer's Tables are founded. The latter received also a reward from the French Government, and gained several prizes for his improvement of the Lunar Theory.—ED.

The fourth refers to the eclipses of the satellites of Jupiter, which would answer the purpose extremely well, had we the means of employing, at sea, telescopes of a certain description, without which they are invisible.

Finally, observations of the moon herself furnish a fifth method, which appears the most practicable, provided we were able to observe the moon's place in the heavens so exactly, that the error in calculation (and error is unavoidable) should never exceed one minute, in order to be assured that we are not mistaken above one degree in the determination of the longitude.*

To one or the other of these five methods persons engaged in this research have chiefly directed their speculations: but there is still a sixth, which seems likewise adapted to the solution of the problem, were it more carefully cultivated; and will perhaps one day furnish us with the most certain method of discovering the longitude; though as yet we are far, very far, short of it.

It is not derived from the heavens, but is attached to the earth simply, being founded on the nature of the magnet, and of the compass. The explication of it opens to me a new field of important physical observation, for your amusement and instruction, on the subject of magnetism; and I flatter myself you will attend with delight and improvement to the elucidations which I am going to suggest.

My reflections shall be directed only to the main subject of our present research, I mean the discovery of the longitude. I remark in general, that the magnet is a stone which has the quality of attracting iron, and of disposing itself in a certain direction;

* This method is now brought to very great perfection, not only by the improvement of the Lunar Tables, but by the perfection of the sextants and circles with which the Moon's place in the heavens is observed.—Ed.

and that it communicates the same quality to iron and steel, by rubbing, or simply touching them with a magnet; proposing afterwards to enter into a more minute discussion of this quality, and to explain the nature of it.

I begin, then, with the description of a magnetic needle, which, mounted in a certain manner, for the use of mariners, is denominated the *Compass*.

For this purpose, we provide a needle of good steel, nearly resembling *Fig.* 2. of Plate V., one extremity of which B terminates in a point, the better to distinguish it from the other A; it is furnished at the middle C with a small cap, hollowed below, for the purpose of placing the needle on a pivot or point D, as may be seen in the second figure.

The two ends are adjusted in such a manner, that the needle, being in perfect equilibrium, can revolve freely, or remain at rest, on the pivot, in whatever situation it may be placed. Before the magnet is applied, it would be proper to temper the needle, in order to render it as hard as possible; then by rubbing or touching it with a good loadstone, it will instantly acquire the magnetic virtue. The two extremities will no longer balance each other, but the one D will descend, as if it had become heavier; and in order to restore the equilibrium, something must be taken away from the extremity B, or a small weight added to the end A. But the artists, foreseeing this change produced by magnetism, make the end B originally lighter than the end A, that the magnetized needle may of itself assume the horizontal position.

It then acquires another property still more remarkable: it is no longer indifferent to all situations, as formerly; but affects one in preference to every other, and disposes itself in such a manner that the extremity B is directed to the north nearly, and the extremity A toward the south; and the direction of the magnetic needle corresponds almost with the meridian line.

You recollect that, in order to trace a meridian line, which may point out the north and the south, it is necessary to have recourse to astronomical observations, as the motion of the sun and stars determines that direction; and when we are not provided with the necessary instruments, and especially when the sky is overclouded, it is impossible to derive any assistance from the heavens toward tracing the meridian line; this property of the magnetic needle is, therefore, so much the more admirable, that it points out, at all times, and in every place, the northern direction, on which depends the others, toward the east, south, and west. For this reason the use of the magnetic needle, or compass, is become universal.

It is in navigation that the advantages resulting from the use of the compass are most conspicuous; it being always necessary to direct the course of a vessel toward a certain quarter of the world, in order to reach a place proposed, conformably to geographic or marine charts, which indicate the direction in which we ought to proceed. Before this discovery, accordingly, it was impossible to undertake long voyages; the mariner durst not lose sight of the coast, for fear of mistaking his course, unless the sky was unclouded, and the stars pointed out the way.

A vessel on the wide ocean, without the knowledge of the proper course, would be precisely in the state of a man who, with a bandage over his eyes, was obliged to find his way to the great church of Magdeburg; imagining he was going one way, he might be going another. The compass, then, is the principal guide in navigation; and it was not till after

this important discovery that men ventured across the ocean, and attempted the discovery of a new world. What would a pilot do without his compass during or after a storm, when he could derive no assistance from the heavens? Take whatever course he might, he must be ignorant in what direction he was proceeding, north, south, or to any other quarter. He would presently deviate to such a degree, as infallibly to lose himself. But the compass immediately puts him right; from which you will be enabled to judge of the importance of the discovery of the magnetic needle, or mariner's compass.

6th October **1761.**

Letter LV.—Declination of the Compass, and Manner of Observing It.

Though the magnetic needle affects the situation of being directed from south to north, there are accidental causes capable of deranging this direction, which must be carefully avoided. Such are the proximity of a loadstone, or of iron or steel. You have only to present a knife to a magnetic needle, and it will immediately quit its natural direction, and move toward the knife; and, by drawing the knife round the needle, you will make it assume every possible direction. In order to be assured, then, that the needle is in its natural direction, you must keep at a distance from it all iron or steel, as well as magnets; which is so much the more easy, that these substances influence its direction only when very near it: once removed, their effect becomes insensible, unless in the case of a very powerful magnet, which might possibly act on the needle at the distance of several feet.

But iron alone produces not this effect, as the compass may be used to advantage even in iron mines. You are perfectly sensible, that under ground, in mines, we are in the same condition as at sea when the face of heaven is overclouded, and that it is necessary to drive mines in a certain direction. Plans are accordingly constructed representing all the tracks hollowed out in the bowels of the earth, and this operation is regulated merely by the compass; this is the object of the science denominated subterraneous geometry.

To return to our compass, or magnetic needle, I have remarked that its direction is only almost northerly; it is therefore incorrect to say that the magnet has the property of always pointing north. Having employed myself in the fabrication of many magnetic needles, I constantly found that their direction at Berlin deviated about 15° from the true meridian line; now, an aberration of 15° is very considerable.

Figure 3. Plate V. represents first the true meridian line drawn from north to south; that which is drawn at right angles with it indicates the east to the right hand, and the west to the left. Now the magnetic needle AB does not fall on the meridian, but deviates from it an angle 15° BO *North*. This angle is denominated the *declination*, and sometimes the *deviation* or *variation*, of the compass or magnetic needle; and as the extremity B, nearest the north, deviates toward the west, we say the declination is 15° westerly.

Having thus determined the declination of the magnetic needle, we can make it answer the same purpose as if it pointed directly north. The needle is usually enclosed in a circle, and you have only to mark on it the due north at the exact distance from the northern extremity of the needle, so as to make

a declination of 15° westward; and the line *North South*, Fig. 3, will indicate the true meridian line, and enable us to ascertain the four cardinal points, north, east, south, and west.

The better to disguise the secret, the magnetic needle is concealed in a circle of pasteboard, as represented in the figure, only the needle is rendered invisible, the pasteboard covering it, and forming but one body with it, the centre of which is placed on a pivot,* in order to admit of a free revolution: it assumes, of course, a situation such that the point marked *North* is always directed to that point of the horizon; whereas the needle, which is not seen, in effect deviates from it 15° to the west. This construction serves only to disguise the declination, which the vulgar consider as a defect, though it be rather an object worthy of admiration, as we shall afterwards see; and the pasteboard only increasing the weight of the needle, prevents its turning so freely as if it were unencumbered.

To remedy this, and more commodiously to employ the compass, the needle is deposited in a circular box, the circumference of which, divided into 360°, exhibits the names of the principal points of the horizon. In the centre is the pivot or point which supports the needle, and this last immediately assumes a certain direction; the box is then turned till the northern extremity of the needle B exactly corresponds with 15° on the circumference, reckoning from the north-westward; and then the names marked will agree with the real quarters of the world.

At sea, however, they employ needles cased in circles of pasteboard, the circumference of which is divided into 360°, to prevent the necessity of turning

* The cap or hollow which rests on the pivot should be made of Garnet, which gives less friction than any other of the precious stones.—Ed.

round the box; then the pasteboard circle, which is called the compass, indicating the real quarters of the world, we have only to refer to it the course which the ship is steering, in order to ascertain the direction, whether north or south, east or west, or any other intermediate point. By the compass likewise we distinguish the winds, or the quarters from which they blow; and from the points marked on it their names are derived. It is necessary, at any rate, to be perfectly assured of the declination or variation of the compass; we have found it to be exactly 15° westward here at Berlin; but it may be different at other places, as I shall afterwards demonstrate.

10th October 1761.

Letter LVI.—Difference in the Declination of the Compass at the same Place.

When I say that the declination of the compass is 15° west, this is to be understood as applying only to Berlin, and the present time; for it has been remarked, that not only is this declination different at different places of the earth, but that it varies, with time, at the same place.*

The magnetic declination is accordingly much greater at Berlin now, than it was formerly. I recollect the time perfectly when it was only 10°;† and in the last century there was a period when there was no declination, so that the direction of the magnetic needle coincided exactly with the meridian line. This was about the year 1670; since then the

* In the year 1786, M. Schulze found the deviation to be 18° 28′, which seems to have been its maximum. In 1805, M. Bode found it to be 18° 3′, having been so low as 17° 5′ in 1788.—Ed.

† It was so low as 10° at Berlin in 1717.—Ed.

declination is become progressively greater toward the west, up to 15°, as at this day: and there is every appearance that it will go on diminishing, till it is again reduced to nothing. I give this, however, merely as conjecture, for we are very far from being able to predict it with certainty.

Besides, it is well known, that prior to the year 1670, the declination was in the contrary direction, that is, toward the east; and the farther back we go, the greater do we find the declination eastward. Now, it is impossible to go farther back than to the period when the compass was discovered; this happened in the fourteenth century; but it was long after the discovery before they began to observe the declination at Berlin; for it was not perceived at first that the needle deviated from the meridian line.

But at London, where this subject has been more carefully studied, the magnetic declination, in the year 1580, was observed to be 11° 15′ east; in 1622, 6° 0′ east; in 1634, 4° 5′ east; in 1657 there was no declination; but in 1672 it was 2° 30′ west; in 1692, 6° 0′ west; and at present it may probably be 18 degrees west, or more.* You see, then, that about the beginning of the last century, the declination was nearly 8 degrees east: that thenceforward it gradually diminished, till it became imperceptible in the year 1657; and that it has since become westerly, gradually increasing up to the present time.

It has preserved nearly the same order at Paris; but there it was reduced to nothing in 1666, nine years later than at London: hence you will observe a most unaccountable diversity of declination relatively to different places of the earth at the same time, and to the same place at different times.

* In January 1821, the variation of the Needle at London, was 24° 35′ west.—Ed.

At present, not only through all Europe, but through all Africa, and the greatest part of Asia, the declination is westerly, in some places greater, in others less, than with us. It is greater in certain countries of Europe than at our capital; namely, in Scotland and in Norway, where the declination considerably exceeds 20°; in Spain, Italy, and Greece, on the contrary, it is less, being about 12°; on the western coasts of Africa it is about 10°, and on the eastern 12°. But as you advance eastward into Asia it progressively diminishes, till it entirely disappears in the heart of Siberia, at Jeniseisk; it disappears too in China, at Pekin, and at Japan; but beyond these regions, to the eastward, the declination becomes easterly, and goes on increasing in this direction, along the north part of the Pacific Ocean, to the western coasts of America, from which it proceeds gradually diminishing, till it again disappears in Canada, Florida, the Antilles, and toward the coasts of Brazil. Beyond these countries, toward the east, that is, toward Europe and Africa, it again becomes westerly, as I have already remarked.

In order to attain a perfect knowledge of the present state of magnetic declination, it would be necessary to ascertain for all places, both at land and sea, the present state of magnetic declination, and whether its tendency is westward or eastward. This knowledge would be undoubtedly extremely useful, but we dare scarcely hope for it. It would require men of ability in every part of the globe, employed at the same time in observing, each on his own station, the magnetic declination, and who should communicate their observations with the utmost exactness. But the space of some years would elapse before the communications of the more remote could be received; thus the knowledge aimed at is unattainable till after the expiration of years. Now, though no

very considerable change takes place in the direction of the magnetic needle in two or three years, this change, however small, would however prevent the attainment of complete information respecting the present state of the various declinations of the magnetic needle, from observations made at the same time in the different regions of the globe.

The same thing holds with respect to times past; to every year corresponds a certain state of magnetic declination proper to itself, and which distinguishes it from every other period of time, past and future. It were, however, sincerely to be wished, that we had an exactly detailed state of the declination for one year only; the most important elucidations of the subject would certainly be derived from it.

The late *Mr. Halley*, a celebrated English astronomer, has attempted to do this for the year 1700, founding his conclusions on a great number of observations made at different places, both by land and sea; but beside that some very considerable districts, where these observations were not made, are not taken into his account, most of those which he has employed were made several years prior to 1700; so that at this era the declination might have undergone very considerable alterations. It follows, that this statement, which we find represented on a general chart of the earth, must be considered as extremely defective; and, moreover, what would it now avail us to know the state of magnetic declination for the year 1700, having since that time undergone a considerable change?

Other English geographers have produced, posterior to that period, a similar chart, intended to represent all the declinations, such as they were in the year 1744. But as it has the same defect with that of *Mr. Halley*, and as they likewise were unable to procure observations from several countries on the globe, they did not scruple to fill up the vacant places, by consulting *Halley's* chart, which certainly could not apply to 1744. You will conclude, from what I have said, that our knowledge of this important branch of physics is extremely imperfect.*

13*th October* 1761.

Letter LVII.—Chart of Declinations; Method of employing it for the Discovery of the Longitude.

It may be proper likewise to explain in what manner *Halley* proceeded to represent the magnetic declinations, in the chart which he constructed for the year 1700, that if you should happen to see it, you may comprehend its structure.

First, he marked at every place the declination of the magnetic needle, such as it had been there observed. He distinguished, among all these places, those where there was no declination, and found that they all fall in a certain line, which he calls the *line of no declination*, as every where under that line there was then none. This line was neither a meridian nor a parallel, but run in a very oblique direction over North America, and left it near the coasts of Carolina; thence it bent its course across the Atlantic Ocean, between Africa and America. Beside this line, he discovered likewise another in which the declination disappeared; it descended through the middle of China, and passed from

* Very correct and interesting charts, both of the variation and the dip of the magnetic needle, have been recently constructed by Mr. Hansteen of Christiania in Norway, and published in his very able work on the Magnetism of the Earth. Mr. Hansteen's charts will be found in the *Edinburgh Philosophical Journal*, vol. iv. p. 363.—Ed.

thence through the Philippine Isles and New Holland. It is easy to judge, from the track of these two lines, that they have a communication near both poles of the globe.

Having fixed these two lines of no declination, *Mr. Halley* remarked, that every where between the first and last, proceeding from west to east, that is, through all Europe, Africa, and almost the whole of Asia, the declination was westerly; and that on the other side, between those lines, that is, over the whole Pacific Ocean, it was easterly. After this, he observed all the places in which the declination was 5 degrees west, and found he could still conveniently draw a line through all these places, which he calls the *line of five degrees west*. He found likewise two lines of this description, the one of which accompanied, as it were, the first of no declination, and the other the last. He went on in the same manner with the places where the declination was 10°; afterwards 15°, 20°, &c., and he saw that these lines of great declination were confined to the polar regions; whereas those of small declination encompassed the whole globe, and passed through the equator.

In fact, the declination scarcely ever exceeds 15° on the equator, whether west or east; but on approaching the poles, it is possible to arrive at places where the declination exceeds 58° and 60°. There are undoubtedly some where it is still greater, exceeding even 90°, and where the northern extremity of the needle will consequently turn about and point southward.*

* This was found to be the case in the voyages of Captain Ross and Captain Parry. On the S.E. point of Byam Martin's Island, in West Long. 103° 44′½, and North Lat. 75° 9′, the variation was 165° 50′ east, having been 128° 50′ west in West Long. 91° 47′, and North Lat. 74° 40′.—Ed.

Finally, having drawn similar lines through the places where the declination was eastward 10°, 15°, 20°, and so on, *Mr. Halley* filled up the whole chart, which represented the entire surface of the earth, under each of which lines the declination is universally the same, provided the observations are not erroneous. *Mr. Halley* has accordingly scrupulously abstained from continuing such lines beyond the places where observations had actually been made: for this reason the greater part of his chart is a blank.

Had we such a chart accurate and complete, we should see at a glance what declination must have predominated at each place at the time for which the chart was constructed; and though the place in question should not be found precisely under one of the lines traced on the chart, by comparing it with the two lines between which it might be situated, we could easily calculate the intermediate declination which corresponds to it. If I found my present place to be between the lines of 10° and 15° of western declination, I should be certain that the declination there was more than 10°, and less than 15°; and according as I might be nearer the one or the other, I could easily find the means which would indicate the true declination.

From this you will readily comprehend, that if we had such a chart thus exact, it would assist us in discovering the longitude, at least for the time to which it corresponded. In order to explain this method, let us suppose that we are possessed of a chart constructed for the present year, we would see on it, first, the two lines drawn through the places where there is no declination; then the two where it is 5°, 10°, 15°, 20°, both east and west: let us farther suppose that, for the greater exactness, these lines were drawn from degree to degree, and that I found

myself at a certain place on sea, or in an unknown country, I would in the first place draw a meridian line, in order to ascertain how much my compass deviated from it, and I should find, for example, that the declination is precisely 10° east; I should then take my chart, and look for the two lines under which the declination is 10° east, fully assured that I am under the one or the other of these two lines, which must at once greatly relieve my uncertainty. Finally, I would observe the height of the pole, which being the latitude of my place, nothing more would remain but to mark, on the two lines mentioned, the points where the latitude is the same with that which I have just observed, and then all my uncertainty is reduced to two points very distant from each other; now the circumstances of my voyage would easily determine which of those two places is that where I actually am.

You will admit that if we had charts such as I have described, this method would be the most commodious and accurate of all for ascertaining the longitude; but this is precisely the thing we want; and as we are still very far from having it in our power to construct one for the time past, which would be of no use for the present time, for want of a sufficient number of observations, we are still less instructed respecting all the changes of declination which every place undergoes in the lapse of time. The observations hitherto made assure us, that certain places are subject to very considerable variations, and that others scarcely undergo any, in the same interval of time; which strips us of all hope of ever being able to profit by this method, however excellent it may be in itself.

17th October 1761.

Letter LVIII.—Why does the Magnetic Needle affect, in every place of the Earth, a certain direction, differing in different places; and for what reason does it change, with time, at the same place?

You will undoubtedly have the curiosity to be informed why magnetic needles affect, at every place on the globe, a certain direction; why this direction is not the same at different places; and why, at the same place, it changes with the course of time? I shall answer these important inquiries to the best of my ability, though, I fear, not so much to your satisfaction as I could wish.

I remark, first, that magnetic needles have this property in common with all magnets, and that it is only their form, and their being made to balance and revolve freely on a pivot, which renders it more conspicuous. The loadstone, suspended by a thread, turns toward a certain quarter, and when put in a small vessel to make it swim on water, the vessel which supports the loadstone will always affect a certain direction. Every loadstone fitted with two opposite points, the one of which is directed to the north, and the other to the south, will be subject to the same variations as the magnetic needle.

These points are very remarkable in all loadstones, as by them iron is attracted with the greatest force.

They are denominated the *poles* of a loadstone—a term borrowed from that of the poles of the earth, or of the heavens; because the one has a tendency toward the north, and the other toward the south pole of the earth: but this is to be understood as only almost, not exactly, the case; for when the name was imposed, the declination had not yet been observed. That pole of the loadstone which is directed northward is called its north pole, and that which points southward its south pole.

I have already remarked, that a magnetic needle, as well as the loadstone itself, assumes this situation, which appears natural to it only when removed from the vicinity of another loadstone, or of iron. When a magnetic needle is placed near a loadstone, its situation is regulated by the poles of that loadstone: so that the north pole of the loadstone attracts the southern extremity of the needle; and reciprocally, the south pole of the loadstone the northern extremity of the needle. For this reason, in referring one loadstone to another, we call those the friendly poles which bear different names, and those the hostile which have the same name. This property is singularly remarkable on bringing two loadstones near each other; for then we find, that not only do the poles of different names mutually attract, but that those of the same name shun and repel each other. This is still more conspicuous when two magnetic needles are brought within the sphere of mutual influence.

In order to be sensible of this, it is of much importance to consider the situation which a magnetic needle assumes in the vicinity of a loadstone.

The bar AB (Plate V. *Fig.* 4.) represents a loadstone, whose north pole is B, and the south pole A: you see various positions of the magnetic needle, under the figure of an arrow, whose extremity marked *b* is the north pole, and *a* the south. In all these positions, the extremity *b* of the needle is directed toward the pole A of the loadstone; and the extremity *a* to the pole B. The point *c* indicates the pivot on which the needle revolves; and you have only to consider the figure with some attention, in order to determine what situation the needle will assume, in whatever position round the loadstone the pivot *c* is fixed.

If there were, therefore, any where a very large loadstone AB, the magnetic needles placed round it would assume at every place a certain situation, as we see actually to be the case round the globe. Now if the globe itself were that loadstone, we should comprehend why the magnetic needles every where assumed a certain direction. Naturalists, accordingly, in order to explain this phenomenon, maintain that the whole globe has the property of a magnet, or that we ought to consider it as a prodigious loadstone. Some of them allege, that there is at the centre of the earth a very large loadstone, which has exercised its influence on all the magnetic needles, and even on all the loadstones, which are to be found on the surface of the earth; and that it is this influence which directs them in every place, conformably to the directions which we observe them to assume.

But there is no occasion to have recourse to a loadstone concealed in the bowels of the earth. Its surface is so replenished with mines of iron and loadstone, that their united force may well supply the want of this huge magnet. In fact, all loadstones are extracted from mines—an infallible proof that these substances are found in great abundance in the bowels of the earth, and that the union of all their powers furnishes the general force which produces all the magnetical phenomena. We are likewise enabled thereby to explain, why the magnetic declination changes, with time, at the same place; for it is well known, that mines of every kind of metal are subject to perpetual change, and particularly those of iron, to which the loadstone is to be referred. Sometimes iron is generated, and sometimes it is destroyed at one and the same place; there are

accordingly at this day mines of iron where there were none formerly; and where it was formerly found in great abundance, there are now hardly any traces of it. This is a sufficient proof that the total mass of loadstones contained in the earth is undergoing very considerable changes, and thereby undoubtedly the poles, by which the magnetic declination is regulated, likewise change with the lapse of time.

Here, then, we must look for the reason why the magnetic declination is subject to changes so considerable at the same places of the globe. But this very reason, founded on the inconstancy of what is passing in its bowels, affords no hope of our ever being able to ascertain the magnetic declination beforehand, unless we could find the means of subjecting the changes of the earth to some fixed law. A long series of observations, carried on through several ages successively, might possibly throw some light on the subject.

20*th October* 1761.

Letter LIX.—Elucidations respecting the cause and variation of the Declination of Magnetic needles.

Those who allege that the earth contains in its womb a prodigious loadstone, like a stone with a kernel in fruit, are under the necessity of admitting, in order to explain the magnetic declination, that this stone is successively shifting its situation. It must in that case be detached from the earth in all its parts; and as its motion would undoubtedly follow a certain law, we might flatter ourselves with the hope of one day discovering it. But whether there be such a magnetic stone within the earth, or whether the loadstones scattered up and down through its entrails unite their force to produce the magnetical phenomena, we may always consider the earth itself as a loadstone, in subserviency to which every particular loadstone, and all magnetic needles, assume their direction.

Certain naturalists have enclosed a very powerful magnet in a globe, and having placed a magnetic needle on its surface, observed phenomena similar to those which take place on the globe of the earth, by placing the magnet within the globe, in several different positions. Now, considering the earth as a loadstone, it will have its magnetic poles, which must be carefully distinguished from the natural poles round which it revolves. These poles have nothing in common between them but the name; but it is from the position of the magnetic poles, relatively to the natural, that the apparent irregularities in the magnetic declination proceed, and particularly of the lines traced on the globe, of which I have endeavoured to give you some account.

In order more clearly to elucidate this subject, I remark, that if the magnetic poles exactly coincided with the natural, there would be no declination all over the earth; magnetic needles would universally point to the north precisely, and their position would be exactly that of the meridian line. This would no doubt be an unspeakable advantage in navigation, as we should then know with precision the course of the vessel and the direction of the wind; whereas, at present, we must always look for the declination of the compass before we are able to determine the true quarters of the world. But then the compass could furnish no assistance toward ascertaining the longitude, an object which the declination may sooner or later render attainable.

Hence it may be concluded, that if the magnetic poles of the earth differed very greatly from the natural, and that if they were directly opposite to each other—which would be the case if the magnetic axis of the earth, that is, the straight line drawn from the one magnetic pole to the other, passed through the centre of the earth—then magnetic needles would universally point toward these magnetic poles, and it would be easy to assign the magnetic direction proper to every place; we should only have to draw for every place a circle which should at the same time pass through the two magnetic poles, and the angle which this circle would make with the meridian of the same place must give the magnetic declination.

In this case, the two lines under which there is no declination, would be the meridians drawn through the magnetic poles. But as we have seen that, in reality, these two lines without declination are not meridians, but take a very unaccountable direction, it is evident that no such case actually takes place. *Halley* clearly saw this difficulty, and therefore thought himself obliged to suppose a double loadstone in the bowels of the earth, the one fixed, the other moveable; of consequence, he was obliged to admit four poles of the earth, two of them toward the north and two toward the south, at unequal distances. But this hypothesis seems to me rather a bold conjecture: it by no means follows, that because these lines of no declination are not meridians, there must be four magnetic poles on the earth; but rather, that there are only two, which are not directly opposite to each other; or, which comes to the same thing, that the magnetic axis does not pass through the centre of the earth.

It remains, therefore, that we consider the cases in which these two magnetic poles are not directly opposite, and in which the magnetic axis does not pass through the centre of the earth; for if we embrace the hypothesis of the magnetic nucleus within the earth, why should one of its poles be precisely opposite to the other? This nucleus may very probably be not exactly in the very centre of the earth, but at a considerable distance from it. Now, if the magnetic poles are not diametrically opposite to each other, the lines of no declination may actually assume a direction similar to that which, from observation, we find they do; it is even possible to assign to the two magnetic poles such places on the earth, that not only these lines should coincide with observation, but likewise, for every degree of declination, whether western or eastern, we may find lines precisely similar to those which at first seemed so unaccountable.

In order, then, to know the state of magnetic declination, all that is requisite is to fix the two magnetic poles; and then it becomes a problem in geometry to determine the direction of all the lines which I mentioned in my preceding letter, drawn for every place where the declination is the same: by such means, too, we should be enabled to rectify these lines, and to fill up the countries where no observations have been made; and were it possible to assign, for every future period, the places of the two magnetic poles on the globe, it would undoubtedly prove the most satisfactory solution of the problem of the longitude.

There is no occasion, therefore, for a double loadstone within the earth, or for four magnetic poles, in order to explain the declination of magnetic needles, as *Halley* supposed; but for a simple magnet, or two magnetic poles, provided its just place is assigned to each.* It appears to me, that, from this reflection,

we are much more advanced in our knowledge of magnetism.

24th October 1761.

Letter LX.—Inclination or Dip of Magnetic Needles.

You will please to recollect, that on rubbing a needle against the loadstone, it acquires not only the property of pointing toward a certain point of the horizon, but that its northern extremity sinks, as if it had become heavier, which obliges us to diminish its weight somewhat, or to increase that of the other extremity, in order to restore the equilibrium. I have, without putting this in practice, made several experiments to ascertain how far the magnetic force brought down the northern extremity of the magnetized needle, and I have found that it sunk so as to make an angle of 72 degrees with the horizon, and that in this situation the needle remained at rest. It is proper to remark, that these experiments were made at Berlin about six years ago; for I shall show you afterwards, that this direction to a point below the horizon, is as variable as the magnetic declination.

Hence we see that the magnetic power produces a double effect on needles; the one directs the needle

* The phenomena render it absolutely necessary to admit two magnetic poles. The two northern poles, which we may call B and b, and the two southern poles, A and a, are thus situated, according to Hansteen, in 1823.

	North Lat.		West Long.
B in	69° 34′	and	271° 38′ from Greenwich.
b	85 9		142 11
A	68 48		132 11
a	78 23		223 8

	Years.
The pole B moves round the north pole of the globe in	1740.
——— b, which is weaker than B, in .	860.
——— A moves round the south pole of the globe in	4609.
——— a, which is weaker than A, in .	1304.

See the *Edinburgh Philosophical Journal*, vol. iv. p. 117.—Ed.