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THE ORIGIN OF COMETS.*

ELIS STRÖMGREN.

The University of Chicago has greatly honored me by inviting me to give a lecture on an astronomical subject during my visit to this city.

When I left my country for the United States it certainly was not with the intention of teaching the American astronomers, but on the contrary in order to study and learn myself. American astronomy stands so high that a European astronomer always considers a visit to the United States as an important event in his scientific evolution. When I, to-day, have the opportunity of laying before this audience some results of my own researches in popular form, it is with a strong feeling that what I can offer you today is so very little compared to what I myself have received not only generally at American observatories but especially at the world-famous observatory of the University of Chicago.

All known comets are observed inside our solar system. Our sun is one of the billions of suns which together are called the Milky Way system, and in all probability our Milky Way system is only one of millions and millions again of similar systems.

Our little solar system consists of the sun, the planets with their satellites, and the comets. One of the planets is the earth, a small celestial body, which for most human beings is their whole world. The smallness of the earth and of our solar system in relation to the universe is a scientific matter of fact, which has been proved so long ago that it has become almost a truism. And still I tbink it worth while—in these times—to consider how insignificant everything human is, and how petty are our affairs.

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* A popular lecture given at the University of Chicago November 9, 1917, by Professor Elis Strömgren, Director of the Observatory at Copenhagen, Denmark.

At the meeting of the British Association for the Advancement of Science, held in Manchester in the year 1915, the President of the Association told the following little story:

> An American astronomer, who possessed a powerful telescope, one night received a visit from an ardent politician. It was during a presidential election, Bryan and Taft being the opposing candidates, and feeling ran high. After looking at star clusters and other celestial objects, and having received answers to his various questions, the visitor turned to the astronomer and asked:
>
> "You tell me that every one of these stars is a sun like our own?"
>
> "Yes".
>
> "And that each of them may have a number of planets circulating around them like our sun?"
>
> "Yes."
>
> "And that there may be life on each of these planets?"
>
> The astronomer answered:
>
> "We cannot tell for certain, but it is quite possible that there may be life on many of them."
>
> After pondering for some time the politician rose and said: "It does not matter, after all, whether Taft or Bryan gets in."

I think this is a very good story; it throws a bright light upon the moral which can be drawn from the study of celestial problems.

Of the different celestial bodies we will today occupy ourselves with *the comets*. We will limit ourselves to one question: *Whence do the comets come, and whither do they go? Are they part of our solar system, or are they birds from afar, which only for a short time linger around our little nest?*

As long as man on the whole has been able to meditate upon things above his immediate range, these questions have always possessed a great attraction for the imagination. For a long time the opinions of the astronomers on this point have been divided and changing, but to-day we are able to give a positive answer to the question of the origin of comets.

We are all familiar with the appearance of a comet. The principal parts are the head, with the nucleus within it, and the tail. But today we are not going to deal with the appearance or with the physical and chemical conditions of the comets. I am going to talk about the *origin* of comets, and this question is connected with the question of the *orbits* of the comets.

Until the days of Tycho Brahe it was believed that the comets were phenomena in the atmosphere of the earth. Tycho Brahe succeeded in proving that the comets are celestial objects, but a real determination of the orbits of comets in space was first made after *Newton* had discovered his law of universal *gravitation.*

This law, the law of gravitation, is the basis for all computations of orbits of celestial bodies, and without an understanding of the contents of this law it is not possible to understand a discussion of the problem of celestial movements.

Popularly expressed and applied to astronomical problems this law says:

Wherever there are two celestial bodies, there always is a force of attraction working between the two bodies. And with regard to the intensity of this force, the law says that it is greater the bigger the two masses are and the closer they are to each other.

We are all familiar with the method by which one can demonstrate the effect of this force upon two heavenly bodies, for instance the sun and the earth.

The result is that the small body, the earth, must travel in an oval orbit around the large body, the sun.

Such *is* the orbit of the earth, and such *are* the orbits of the other planets also.

That the force of gravitation exists there is no doubt. It is there, and it is working all the time and everywhere, wherever there is matter.

By this force it is possible to explain all the motions of the celestial bodies, even to the finest details, *but* are we able to explain the force itself?

Here we touch upon the darkest point of the whole astronomical science.

How difficult this question is, was clearly illustrated a few years ago by a prominent English astronomer. While speaking of the attempts of modern physicists to construct models of atoms, which should be able to explain the different qualities of matter, he said:

"If a new model of the atom is put forward, we ask if it accounts for the Zeeman-effect, for chemical affinity, for the dispersion of light, and a host of incidental phenomena; but it would be considered *unfair* to suggest that it ought to account for the *one fundamental and universal property of matter, gravitation.*"

But the force *is* there. And we know how by the aid of this force we are able to explain the shape of the planetary orbits.

A mathematical investigation of the problem, however, shows that there is a possibility of two other kinds of orbits in the problem of two bodies.

The orbits we have spoken of are called *ellipses.*

The other two kinds of orbits which are possible in the problem of two bodies are called the *parabola* and the *hyperbola* (see Fig. 1).

The essential difference between these two kinds of orbits (parabola and hyperbola) on the one side, and the ellipse on the other, is that the ellipse is a closed curve, and the parabola and the hyperbola are open with branches of indefinite extent.

This means in other words:

> An elliptic orbit of a comet indicates that the comet belongs to our solar system; a parabolic or a hyperbolic orbit indicates that the comet comes from without, from interstellar space.

Thus the whole question of the origin of comets seems very simple: if we put together in a table all computed comet orbits, we find that there are a certain number of hyperbolas and parabolas and another number of ellipses; from which we might draw the conclusion that some of the comets have come from without and that some of them belong to our solar system.

Yes—the problem seemed to be very simple, and it was treated in this simple way until about twenty years ago.

But we are now going to see that the problem is in reality much more complicated.

When speaking about the "problem of two bodies" and the explanation of the orbits of the planets and the comets, we intentionally neglected one point which is of great importance when we have to make *exact* calculations.

We know how the sun's attraction causes a planet, for example the *earth*, to make an ellipse around the sun. We can in the same way show how the planet Mars follows a similar orbit around the sun.

But in reality, in addition to the attractions between the sun and the earth and between the sun and Mars, there is also a mutual attraction between the *earth and Mars*, and, despite its comparative insignificance, this force causes deviations from the purely elliptical orbits of the two planets. Such small deviations from the simple ellipse are called *perturbations.*

The computation of the *perturbations* in the motions of the planets has for two centuries been the chief problem in theoretical astronomy.

But now we arrive at the important point in the cometary problem.

The orbit, which is computed with the aid of the observations of a comet, is in fact only valid for a certain period of time—the period during which the comet has been observed, that is, in the vicinity of the perihelion of the orbit—for the obvious reason that the comet is not visible from the earth beyond a certain distance from the perihelion, both coming and going (see Fig. 1).

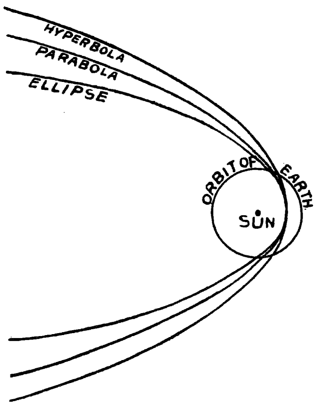

FIGURE 1.

In this way, with the help of a very small section of the orbit, one orbit after the other was computed. In the course of time we obtained a table of several hundreds of cometary orbits. And this table formed the basis for all conclusions drawn in regard to the origin of comets.

Nobody ever raised the question as to whether the innermost part of the cometary orbit really is a true expression of the way in which the comet *originally* entered into the interior parts of our solar system.

It was not until about twenty years ago that this simple question was raised: Have not the great planets of our solar system had a noticeable influence upon the orbits of the comets during the long time needed for coming into the interior parts of our solar system? Is it not possible that this influence can be so great as to change an originally elliptic orbit into a hyperbolic one and vice versa?

If this be the case, must not the problem of the origin of comets be taken up anew?

Let us look more accurately into the matter.

Amongst the various qualities which characterize an ellipse, a parabola, or an hyperbola, there is one which is particularly important for our problem. It is that which we might term *the degree of elongation.* It is called by astronomers and mathematicians the *eccentricity* of the orbit and is designated by the letter e.

In order to obtain a concrete impression, we give the following figures:

1. A circle has no elongation. We say the eccentricity $e = 0$.
2. The ellipse can for e have all possible values between 0 and 1.
3. The parabola has $e = 1$.
4. The hyperbola has e greater than 1.

If then with the aid of our observations we have calculated the orbit of a comet and obtained the result

$$e = 0.999500,$$

this would mean that the orbit is elliptic; and if we obtained the result

$$e = 1.000500,$$

this would mean that the orbit is hyperbolic.

Now amongst our calculated cometary orbits we really have a great many cases where the eccentricities lie in the neighborhood of unity, the most a little less than 1, the remainder a little more. And we now know from the preceding what a fundamental difference there is from a cosmogonic point of view between the cometary orbits where the eccentricity is a little less than 1 and those cases where it is a little more. In the former case the comet would belong to our solar system —in the latter it would have come from the outside.

But now we again come back to our original starting point: that orbit which has been calculated by our observations, i.e., by the help of the innermost part of the orbit, cannot be exactly the same as that orbit which the comet had in the outer parts of the solar system.

Then calculate the perturbations and see what eccentricity the orbit had when the comet was far away.

This investigation has been made during the last twenty-two years*, and the results may be summarized in the following way:

If we follow the different comets backwards for a sufficient time, we find that there is not one single hyperbola left. Those comets, which in the interior part of the solar system have shown a hyperbolic orbit, have received this hyperbolic shape through the perturbations by the planets.

This is the answer to the question of the origin of comets: the comets belong to our solar system, and, where the astronomers previously believed they had to differentiate between *periodical* and *non-periodical* comets, we now only speak of *short-period* and *long-period* comets.

Here we have a piece of cosmogony, the cosmogony of comets. It carries us far back in time. Those comets that have the most extended orbits need hundreds of thousands of years to go around the sun.

But, as my audience knows, the astronomers have set up cosmogonic theories which carry us back into, not hundreds of thousands, but millions and billions of years.

The striking likeness between the orbits of the planets led to the famous Kant-Laplacian hypothesis.

The interesting features of the so-called *Spiral Nebula* led *Chamberlin* and *Moulton* to the planetesimal theory, a comprehensive sketch for the whole evolution of celestial bodies and systems of celestial bodies.

Such theories are extremely valuable in astronomy as stimulating to researches in various lines.

* For the development of the problem historically see "Publikationer og mindre Meddelelser fra Köbenhavns Observatorium Nr. 19".

The solution of the question of the *origin of comets*, which we have now put forward, relates to one single problem only. It does not suggest any extensive views or prospectives, nor does it take us either so far back in time as the general cosmogonic theories mentioned above. But our answer to the question of the origin of comets has another quality, which from a certain point of view gives to it a decided preference over most cosmogonic theories: we have arrived at the answer to our problem through exact computation, without any hypothesis and without any assumptions. The only basis for our computation was the law of gravitation, and nobody doubts the existence of this gravitation.

Various arguments against the theory of the comets belonging to our solar system have been put forward.

One has, amongst others, by the help of statistical methods, tried to discover systematic features in the movements of the comets. One has for example discussed the question as to whether the planes of the cometary orbits in space are grouped in a special way—or whether there are special points in the sky from which the comets appear to come preferably. One has believed that such peculiarities in the motions of the comets would show that the comets come into our system from the outside.

But for the first it has been demonstrated (by *Holetschek*) that a great mass of such peculiarities in the movements of the comets are only apparent—in that they can be explained from the conditions of observation from the earth, and for the rest we cannot on the whole imagine any systematic features in connection with the cometary orbits which are not explainable by the theory of the comets belonging to our solar system.

If for example it can be shown that the comets chiefly come to us from certain areas in the sky, it is quite unnecessary to suppose that the comets should have entered our system from the outside from peculiar places in space. It can be explained equally well by the very probable supposition that in places far out *in our nebula* there have existed concentrations of nebular matter which later have gravitated towards the center.

Against the positive proof of the comets belonging to our solar system which we have given today, the existence of such systematic features in the movements of the comets would therefore have no weight.

But now we will try to consider our question in its relation to longer periods of time and to current cosmogonic theories. We came to the conclusion that all known comets are going in elliptic orbits around the sun, and we arrived at this result by an investigation based upon the hitherto calculated cometary orbits. Of course this does not preclude the possibility of a comet coming in from the outside—to-day or in ten thousand years—but up to now we have not been able to point out one single comet which has come from without—from interstellar space.

This is really a very strange result.

There is hardly any astronomer who doubts the leading idea in modern cosmogonic theories, that the celestial bodies and systems of celestial bodies have originated from nebulous matter.

It is quite natural that there still are in existence in our solar system, and especially in the outlying parts of it, such diffuse nebulous matter.

But why do we never discover any comets coming from the space *between the different solar systems*?

Is there no nebulous matter in the immense spaces which separate the different solar systems?

It really seems so, and we will try to indicate a possible explanation

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I will show you a slide: (A globular cluster.)

Thousands or millions of stars gathered into a system of approximately globular form. Such a system is called a *globular cluster.*

Here is another photograph: (A Spiral Nebula).

A so-called Spiral Nebula. However, these spiral nebulæ are no nebulæ at all, but conglomerations of thousands or millions of stars.

We know that our own sun is one of millions of suns in a system which is called the Milky Way system, and there are many things which indicate that our Milky Way system is such a spiral nebula.

The distribution of the stars in the globular clusters is of an especially interesting nature: the stars are very much concentrated in the center of the cluster, and gradually thin out towards the outer regions.

Until a few months ago the astronomers had not been able to observe a single case of motion in such a globular cluster. And still we dare say that there is very little in this world which is more certain than that all these stars are in motion, every one of them continually.

Let us assume that for a moment all the stars in such a globular cluster were at rest. We then can be absolutely sure that in the next moment they all would be in motion.

The Newtonian law demands that all these stars attract each other with a force depending on masses and distances.

Let us take a star in the outer regions in the cluster. If this star for a moment were at rest, it instantly would be caught by the collective gravity from all the other stars. It is easy to see that this attraction must be directed towards the center of the cluster.

The star begins to move towards the center. The force is acting all the time in the same direction, and consequently the speed of the star must increase without interruption, until the star has passed the center of the cluster. The star runs over to the other side. The force now is acting in the opposite direction to the motion, and the speed decreases, and after a certain length of time the star stops far out on the other side. The force will now bring the star back again. It passes through the center again, and in this way this star—and all other stars—will keep on traveling in orbits out and in, in and out.

In reality the orbits of the different stars will be much more complicated than that. We assumed that the star had been at rest in a given moment. In such a case it would, as we have seen get a radial motion through the center. But in reality the stars, generally, will also have a component of motion vertical to the line through the center of the cluster. How the movements will show themselves in this more general but also more complicated case is a problem which can be mathematically solved.

In Fig. 2 we have an example of motion in globular clusters under the general conditions.

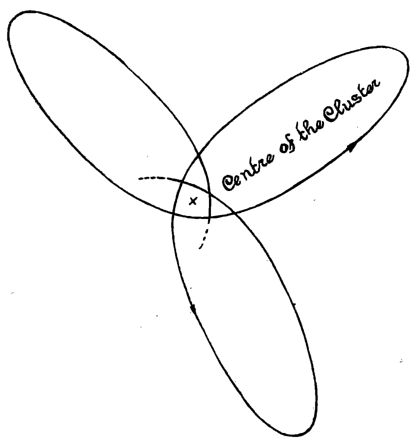

FIGURE 2.

But until now we have neglected an important thing. Until now we have been talking only about the effect of the globular mass *as a whole.* But now and then it will happen that two stars come so close together, that their motions will be entirely altered.

The Newtonian law says: the force of attraction is greater the closer the masses are to each other. Therefore if two stars approach each other closely, their mutual attraction will be so great that it will overcome the attraction of the cluster as a whole, with the result that the orbits of our two stars will be radically changed.

In this connection it is not without interest to note that even in our solar system, in spite of the fact that the masses composing it are so exceedingly small in comparison with one, the sun, movements are found which are quite analogous to the case now alluded to. We have, as a matter of fact, in our solar system examples of comets, the orbits of which, *because of nearness to one or other of the larger planets* have been entirely changed.

Thus we find the motion of the stars in a globular cluster to be this: in the main all the stars are in a motion governed by the collective attraction of the whole cluster, but once in a while two stars get so close together, that both are thrown out of their normal orbits.

This result is very interesting, because we have here a strange analogy to the motions in an entirely different problem of natural science.

I think that all my auditors have an idea about how the physicist explains the conditions operating in the gases: innumerable molecules, which move around and about in the mass, meet each other and disturb each other's orbits, just as we imagine the motions in a globular cluster.

The motions in such a mass of gases can be subjected to a mathematical investigation, and of the results of such an investigation we will mention the following:

In a globular mass of gas the molecules will ultimately arrange themselves in such a way that the mass will be densest in the center and gradually thinner towards the outer regions.

Exactly as is the case with a globular cluster!

But the theory of gases also claims another result:

In a mass of gas the bigger molecules will by and by acquire low velocities and the smaller molecules high velocities.

Let us think of a cluster! It contains millions of stars of different masses, large and small. After a long time the conditions will be such that the largest stars will have low velocities and the smaller masses high velocities.

Let us think of our Milky Way system! We have there the millions of suns with their planets and satellites and more diffuse masses—the comets. But is there *no* nebulous matter, are there no *comets* in the space *between the different solar systems*?

Now, *Charlier* has made the following suggestion, based upon the theorems as to the theory of gases and the globular clusters which we have now pointed out. The diffuse nebulous masses in the space *between* the different solar systems would be the smallest independent masses in our Milky Way system. Consequently they would in the course of time develop the greatest velocities; as a rule they will attain such great velocities *that they will be simply expelled from the Milky Way system.*

Thus the whole situation would be clear, the diffuse nebulous masses *within the solar systems*, in other words *the comets* would on the whole be retained each by the gravitation of its own sun, while those traveling in the space *between* the different solar systems would be driven out from the Milky Way system in the course of time.

We will let the matter rest here.

An exact treatment of the orbits of the comets in our solar system, obtained from observations, has yielded the result that the comets of our solar system actually belong to it, and therefore that they have not wandered in from the outside.

This result has now been accepted by probably all astronomers who have acquainted themselves with the problem. But surprisingly enough, it has required a long time for this simple idea which we have discussed to become established.

It is singular that orbits of hundreds of comets were computed without leading the computers to investigate the influence of the perturbations produced on the original cometary orbits, and this in spite of the fact that the significance of the perturbations on the orbits of *planets* had been well understood for two centuries.

It is related of Charles Darwin that once, in replying to an encouraging letter from a friend in respect to the acceptance of his theory as to the origin of species, he replied that although he certainly believed his theory of the development of species would one day win acceptance, he feared it would take as long a time as the development of species itself had taken.

But it was not as bad as that.

And in *our* problem, the simple thought of the necessity of taking into consideration the effect of the perturbations on the orbits of the comets, when one wishes to draw cosmogonic conclusions, has not taken as long a time to become recognized as is required by the comets of *long* periods to make their circuit around the sun. However, those comets which have the *shortest* periods of revolution had to make many circuits about the sun, before the simple idea, which has been the subject of our consideration, really became clear to the calculators of the orbits of comets!