17. Lozitsky V.G. Spectral manifestations of extremely strong magnetic fields in the sunspot umbra // Advances in Space Research. – 2017. – Vol. 59. – P. 1416–1424.
18. Polupan P.N. Solar installation (Полупан П.Н. Солнечная установка) // Публикации Киевской астрономической обсерватории. – 1962. – № 10. С.59–64.
19. Severny A.B. Calibration of magnetic field signals of a solar magnetograph (Северный А.Б. Калибровка сигналов магнитного поля солнечного магнитографа) // 1967. – Известия КрАО. – Т. 36.– С. 22–50.
20. Shpitalnaya A.A., Vyalshin G.F. About magnetic fields in prominences (Шпитальная А.А., Вяльшин Г.Ф. О магнитных полях в протуберанцах) // Солнечные данные.– 1970, № 4.– С. 100–107.
21. Skomorovsky V.I. Mosaic for magnetic field measurements (Скоморовский В.И. Мозаика для измерения магнитных полей) // В сб.: Исслед. по геомагнетизму, аэрономии и физике Солнца, Вып. 26.– М.: Наука.– 1974.– С. 220–221.
22. Solanki S.K. Sunspots: An overview // Astronomy and Astrophysics Review. – 2003. – Vol. 11.– P. 153–286.
23. Solov'ev, A. A.; Lozitskii, V. G. Force-free model of fine-structure magnetic elements // Kinematika i Fizika Nebesnykh Tel. – 1986. – Vol. 2. – P. 80–84.
24. Stenflo J.O. Magnetic-field structure of the photospheric network // Solar Physics. – 1973. – Vol. 32, No 1. – P. 41–63.
25. Unno W. Line formation of a normal Zeeman triplet // Publ. of Astron. Society of Japan. – 1956. – Vol. 8. P. 108–125.

Надійшла до редколегії 30.06.2021

В. Лозицкий, д-р физ.-мат. наук
Киевский национальный университет имени Тараса Шевченко, Киев, Украина

МАГНИТОГРАФИЧЕСКИЕ И СПЕКТРАЛЬНЫЕ ИССЛЕДОВАНИЯ СОЛНЕЧНЫХ МАГНИТНЫХ ПОЛЕЙ В АСТРОНОМИЧЕСКОЙ ОБСЕРВАТОРИИ КИЕВСКОГО НАЦИОНАЛЬНОГО УНИВЕРСИТЕТА ИМЕНИ ТАРАСА ШЕВЧЕНКО В 1975–1980 гг.

В 1975 г. в Астрономической обсерватории Киевского национального университета имени Тараса Шевченко был установлен и начал действовать магнитограф полного вектора конструкции СибИЗМИР, и это инициировало создание в обсерватории нового перспективного научного направления – измерение солнечных магнитных полей как магнитографическим, так и спектрально-поляризационным методом. В этой статье приведен краткий обзор хронологии событий в первые 5 лет существования нового направления, а также важнейших научных результатов в этот период. В частности, тогда были получены новые данные о существовании магнитных полей напряженностью ≈ 10 кГс в активных областях на Солнце, о дискретности напряженностей в субтелескопичных структурах с очень сильными полями, а также данные о существенном подавлении в них турбулентных движений. Соответствующие выводы были подтверждены и детализированы новыми исследованиями в последующие годы.

Ключевые слова: Солнце, солнечная активность, спектральные исследования, еффект Зеемана, магнитные поля, солнечный магнитограф.

V. Lozitsky, Dr Hab.
Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

MAGNETOGRAPHIC AND SPECTRAL INVESTIGATIONS OF SOLAR MAGNETIC FIELDS IN ASTRONOMICAL OBSERVATORY OF TARAS SHEVVCHENKO NATIONAL UNIVERSITY OF KYIV IN 1975–1980

In 1975, at the Astronomical Observatory of the Taras Shevchenko National University of Kyiv, a magnetograph of the full vector of the SIBIZMIR design was installed and began to operate, and this initiated the creation of a new promising scientific direction at the observatory - the measurement of solar magnetic fields by both magnetographic and spectral-polarization methods. This article provides a brief chronology of the events in the first 5 years of the existence of the new direction, as well as the most important scientific results during this period. Based on the experience of observations obtained at the Kyiv observatory, it was concluded that this magnetograph in the Kyiv's astroclimate can not provide such scientifically valuable data as those magnetographs used in other observatories far outside large cities. In particular, although in Kyiv the sensitivity of measurements in the longitudinal magnetic field channel was quite high – about 5 G in the longitudinal field channel and 75 G in the transverse field channel, "noise" in the radial velocity channel reached 0.3 km/sec, which is about an order of magnitude higher than in the Crimea magnetograph. Another reason for the limited use of the magnetograph in the Kyiv observatory was that in the late 1970s significant problems with the calibration of magnetographic measurements became apparent, as a result of which such measurements in the areas of sunspots could have errors of 200–300%. However, in parallel with magnetographic research, spectral-polarization studies were also developed, and they allowed to obtain the most important results. In particular, the new data were obtained on the existence of magnetic fields with a strength of ≈ 10 kG in active regions on the Sun, on the discreteness of the strengths in subtelescopic structures with very strong fields, as well as data on the significant suppression of turbulent motions in them. The corresponding conclusions were confirmed and detailed by new research in the following years.

Key words: Sun, solar activity, spectral investigations, the Zeeman effect, magnetic fields, solar magnetograph.

УДК 52-44; 521.933

S. Parnovsky, Dr Hab., Prof.
Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

LOSS OF ANGULAR MOMENTUM WHEN THE PLANET'S ATMOSPHERE LEAKS INTO SPACE

In the case of a rotating planet the well-known Jeans mechanism of atmospheric leakage into space leads to a decrease not only in its mass, but also in the angular momentum. We found a constrain linking these losses. On its basis, it is shown that this mechanism could not significantly affect the duration of the Earth's day and its accounting cannot smooth out the problems associated with the theory of the formation of the Moon during the so-called Giant impact, i.e. collision of the protoplanet Theia with the Earth.

Key words: angular momentum, atmospheric leakage, Giant impact.

Introduction. Accurate measurements have shown that the angular velocity of the Earth's rotation is decreasing. The length of a day increases by 23 μs per year. This is due to the transfer of angular momentum from the Earth to the Moon, which for this reason is slowly moving away from the Earth. The distance to the Moon averaged over the period of revolution increases by 38 mm per year. These phenomena were predicted at the end of the 19th century by the English astronomer Sir George Howard Darwin [1]. He also pointed out the reason: the moment of forces arising from the gravitational interaction of tidal waves on the surface of the Earth with the Moon. The fact that in the distant past days were shorter was confirmed by paleontologists when studying fossil corals.

Darwin hypothesized that the Moon was torn away from the Earth by centrifugal forces. However, a simple calculation based on the use of the law of conservation of angular momentum gives an estimate according to which the angular velocity of the Earth's rotation at the moment of the Moon's separation would exceed the existing one five times. It is easy to understand that the speed of rotation of the planet's surface in this case would be significantly lower than the first cosmic (orbital) speed and the Moon could not come off.

Currently, the main hypothesis of the formation of the Moon is the so-called Giant impact hypothesis , according to which the Moon was knocked out of the Earth during a tangential collision with the protoplanet Theia, which was occurred more than 4 billion years ago [2, 3]. It explains the close isotopic composition of the Moon and the Earth, but cannot answer many questions.

When calculating the Giant impact, it is very important to know the speed of rotation of the Earth at the moment of collision. Therefore, the question naturally arises, how constant is the angular momentum of the Earth-Moon system. Naturally, we are not talking about violation of fundamental conservation laws. Is there a mechanism leading to a very slow loss of angular momentum? Over a period of 4 billion years, the influence of any even very weak effect can lead to significant consequences.

Let's try to look for a possible mechanism. The Earth-Moon system is not closed because matter falls from space onto the Earth and atmospheric gases slowly flow into space. The first phenomenon should not lead to a change in the angular momentum. The second is able to reduce it. A rather simple description of the mechanisms of atmospheric loss can be found in the articles [4, 5]. Of these, we are interested in the mechanism considered by James Jeans a hundred years ago [6].

Some molecules of atmospheric gases are capable of leaving the atmosphere and leaking into space. They need for this the speed not less than the escape velocity. In addition, they should not collide with other molecules on its way. The latter can be expressed more simply: the molecule must fly out of the exosphere, where the air density is so low that the molecules are essentially collisionless, i.e. start from a height greater than the height of exosphere lower bound, called exobase. The altitude of the Earth exobase ranges from about 500 to 1000 kilometres above the surface depending on solar activity.

At a height of exobase a length of free path of molecules of the atmospheric gases is comparable with the thickness of the atmosphere. Therefore, molecules with velocities higher than the escape velocity can fly into space. Since the average velocities of thermal motion are significantly less than the escape velocity, then we are talking about the fastest of them, corresponding to the high tail of the Maxwell distribution. The lighter the gas, the greater is the speed of its thermal movement at the same temperature. Therefore, only lighter molecules can have the high speeds required for escape from the atmosphere. In 1 s, the Earth's atmosphere loses about 3 kg of hydrogen and 50 g of helium. They leaks in space at very high altitudes.

It is easy to understand that with a fast rotation of the Earth (as in the period of the Giant impact), much more of fast molecules escape out in the direction of rotation than in the opposite direction. The loss of the atmosphere is accompanied by the loss of the Earth's angular momentum.

In the popular science article [4], some other mechanisms of atmospheric loss are mentioned and explained. Another form of thermal escape is so-called hydrodynamic escape or the planetary wind. The upper atmosphere can absorb solar ultraviolet emission, warm up and expand, pushing air upward. As the air rises, it accelerates smoothly through the speed of sound and then attains the escape velocity. There are also some processes of non-thermal escape.

Some estimation. Let's try to estimate how significant the effect can be over t = 4.5 billion years. I'll start with the simplest estimates. The loss of mass of the atmosphere can be estimated by multiplying its current velocity by t. The resulting estimate $4\cdot10^{17}$ kg is many orders of magnitude less than the mass of the Earth. The angular momentum loss can be estimated by multiplying this value by the escape velocity at the exobase altitude and by the distance from exobase to the centre of Earth. The resulting estimate $3.5\cdot10^{28}$ kg·m^2/s is significantly less than the current angular momentum of the Earth $7\cdot10^{33}$ kg·m^2/s. The angular momentum of the Moon relative to the centre of the Earth is about four times this value.

However, this assessment is too primitive. Note that during 4.5 billion years the composition of the atmosphere, its density and temperature changed. We know little about the parameters of the early Earth's atmosphere, in particular the content of hydrogen and helium in it. Even the angular velocity of rotation changed due to the abovementioned interaction with the Moon. And its increase causes a growth of the rate of leakage of gases with the same parameters.

More accurate estimates can be obtained from the Maxwell distribution, but they still require knowledge of atmospheric parameters in the distant past. However, you can get restrictions that do not require this information. Increasing the temperature, the hydrogen content, or the Earth's rotation speed increases loss rates of both the mass m, and the angular momentum L. Therefore, let's try to link them together. Consider the case of rapid rotation of the Earth, when almost all gases are emitted in only one direction. Let the mass dm flew out of the atmosphere in the direction of planet rotation. In estimation it is possible to accept the speed of emission gases equal to escape velocity V. The maximum possible distance to the axis corresponds to the emission of molecules in the equatorial plane. We assume it equals the radius of the Earth R, neglecting the height of the exobase. The inequality turns out

$$dL \le dmVR\,. \tag{1}$$

Integration gives

$$\Delta L \equiv L - L_0 \le VR\ \Delta m \equiv VR\ (m - m_0)\,. \tag{2}$$

Here Δm and ΔL – changes in the mass and angular momentum of the Earth (or the Earth-Moon system, if we take the Moon into account). Let us denote by the letter ω the angular speed of rotation of the Earth, $v = \omega R$ - the linear speed of rotation at the equatorial plane, and I is the moment of inertia of the Earth. Although the Earth is not homogeneous, one can use the formula for a homogeneous ball to estimate

$$L = I\omega = \frac{2}{5}mR^2\omega = \frac{2}{5}mRv\,. \tag{3}$$

From here

$$\Delta v \le 2.5V\frac{\Delta m}{m}\,. \tag{4}$$

Conclusion. Even if the Earth evaporates by the Jeans mechanism the entire atmosphere weighing about $5 \cdot 10^{18}$ kg, consisting mainly of nitrogen and oxygen, i.e. gases are much heavier than hydrogen and helium, it can be seen from (4) that the change in the linear rotation velocity at the equator will not exceed 2.5 cm/s. And this is the upper limit, not an estimate. As we can see, a comparison of two integral characteristics, namely the loss of mass and angular momentum, allows one to obtain more reliable constraints than a simple estimate of the rates of these losses.

It can be concluded that the leakage of the atmosphere by the Jeans mechanism cannot lead to a significant change in the angular velocity of the Earth's rotation simply because of the insignificance of the mass of the atmosphere. Although it is possible to consider a very exotic assumption that the Earth at the time of formation had a large percentage of chemically bound hydrogen, which was then released into the atmosphere, ensuring a presence of the hydrogen for a long time. The atmosphere constantly flew into space according to the Jeans mechanism, reducing the angular momentum of the Earth. However, this looks like pure speculation.

When considering the Giant impact, one can not assume the possibility of a faster rotation of the Earth. Therefore, the problems inherent in explaining the appearance of the Moon in a collision with the protoplanet Theia cannot be solved due to the loss of angular momentum during the escape of the atmosphere. There are articles that look at other mechanisms. For example, the paper [7] considered how a faster-spinning early Earth-Moon system can lose angular momentum and reach the present state through an orbital resonance between the Sun and Moon.

References

1. Darwin G. H. The tides and kindred phenomena in the Solar System / G. H. Darwin // Boston: Houghton, 1899.
2. Canup R. M. Origin of the Moon in a giant impact near the end of the Earth's formation / R. M. Canup, E. Asphaug // Nature – 2001. – V. 412, p. 708–712.
3. Canup R. M. Forming a Moon with an Earth-like Composition via a Giant Impact / R. M. Canup // Science – 2012. – V. 338, Issue 6110, p. 1052–1055.
4. Catling D. C. The Planetary Air Leak / D. C. Catling, K. J. Zahnle // Scientific American – May 2009, p. 36–43.
5. Heng, K. Atmospheric Escape / K Heng, //In Exoplanetary Atmospheres, Princeton: Princeton University Press, 2017. pp. 211–222.
6. Jeans, J. The Origin of the Solar System / J. Jeans // Nature –1931. – V.128, – p. 432–435.
7. M. Ćuk Making the Moon from a Fast-Spinning Earth: A Giant Impact Followed by Resonant Despinning / M. Ćuk, S.T. Stewart // Science – 2012, – V. 338, Issue 6110, – p. 1047–1052.

Надійшла до редколегії 08.07.2021

С. Парновський, д-р фіз.-мат. наук, проф.
Київський національний університет імені Тараса Шевченка, Київ, Україна

ВТРАТА КУТОВОГО МОМЕНТУ У РАЗІ ВИТІКАННЯ АТМОСФЕРИ ПЛАНЕТИ У КОСМОС

Відомий механізм Джинса витоку атмосфери в космос призводить до зменшення не тільки її маси, але і моменту імпульсу у випадку, коли планета обертається. Знайдено обмеження, що пов'язує ці втрати. На його основі показано, що механізм, який розглядається, не міг істотно вплинути на тривалість земної доби і його внесок не може згладити проблеми, пов'язані з теорією утворення Місяця при зіткненні протопланети Тейя із Землею.
Ключові слова: кутовий момент, виток атмосфери, Гігантське зіткнення.

С. Парновский, д-р физ.-мат. наук, проф.
Киевский национальный университет имени Тараса Шевченко, Киев, Украина

ПОТЕРЯ МОМЕНТА ИМПУЛЬСА ПРИ УТЕЧКЕ АТМОСФЕРЫ ПЛАНЕТЫ В КОСМОС

Известный механизм Джинса утечки атмосферы в космос в случае вращающейся планеты приводит к уменьшению не только ее массы, но и момента импульса. Найдено ограничение, связывающее эти потери. На его основе показано, что этот механизм не мог существенно повлиять на продолжительность земных суток и его вклад не может сгладить проблемы, связанные с теорией образования Луны при столкновении протопланеты Тейя с Землей.
Ключевые слова: момент импульса, утечка атмосферы, Гигантское столкновение.