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AURORAS DURING EXTREME GEOMAGNETIC STORMS: VISUAL OBSERVATIONS OF THE SAR ARC IN IRKUTSK DURING THE 1859 CARRINGTON EVENT

A.V. Mikhalev
Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, mikhalev@iszf.irk.ru

A.B. Beletsky
Institute of Solar-Terrestrial Physics SB RAS, Irkutsk, Russia, beletsky@mail.iszf.irk.ru

Abstract. The paper analyzes the description in chronicles of the September 2, 1859 auroras observed in Irkutsk during the Carrington event. The description of the red arc by an eyewitness, the analysis of geomagnetic conditions, publications on visual observations of auroras of various forms at middle and low latitudes during this period, modern instrumental observations of SAR arcs at the latitude of Irkutsk have allowed us to assume that the red arc described in the chronicles is a SAR arc — one of the auroral types at subauroral and middle latitudes observed during geomagnetic storms. We have established that in Irkutsk the SAR arc was observed during the recovery phase of the magnetic superstorm. The intensity of the SAR arc was estimated at ~10–20 kR. The projection of the plasmapause onto the ionosphere on September 2, 1859 at ~12 UT was at the latitude of Irkutsk. We can assume that the description of the aurora borealis on September 2, 1859 in Irkutsk is the first objective description of the SAR arc, a century before its discovery as a phenomenon in 1958.

Keywords: Carrington event, auroras, SAR arc, mid-latitude airglow.

INTRODUCTION

The observed global climate changes, as well as the possible role of solar activity variations in them, have aroused great interest in extreme natural events of the past centuries (see, e.g., [Kataoka et al., 2019; Knipp et al., 2021; Berrilli, Giovannelli, 2022]). A closer study of such events, taking into account the modern understanding of physical processes and phenomena, can be useful for their correct interpretation. This fully applies to extreme magnetic storms and great auroras.

In this regard, the eyewitness's description of the mid-latitude aurora observed in Irkutsk on August 21, 1859 (old style) is of interest. [Chernigov, 2003]: "At about 7 p.m., a red light cloud was seen in the northwest, and then a red arc formed which passed through the zenith from the northwest to the southeast. At ~8 p.m., a pale white light appeared in the north, a precursor of the aurora borealis. It turned from white to bright silver, and there soon occurred divergent red and white rays on it. The arc that usually produces the diverging columns was not visible. It was either below the horizon or covered by clouds. With the appearance of the columns, the red arc changed direction: one its end was in the west; and the other, in the east; the top passed through the zenith. It had the same width everywhere, like a rainbow, only red color; at 10:15 p.m., the aurora borealis ended and the arc disappeared. The northern lights were occasionally observed in Irkutsk, but this phenomenon was never accompanied by a red arc passing through the zenith until this year."

It is clear to specialists dealing with auroras that the described red arc may correspond to such a phenomenon as the SAR arc, the type of aurora at subauroral and middle latitudes discovered by D. Barbier in 1958 [Barbier, 1959]. SAR arcs are a relatively rare optical phenomenon observed at subauroral latitudes during geomagnetic storms. The main emission is in the forbidden lines of the atomic oxygen doublet [OI] at 630.0 and 636.4 nm with a characteristic intensity from hundreds of Rayleighs to several kilorayleighs. SAR arcs correlate with geomagnetic activity and are generally seen during the recovery phase of magnetic storms [Kozyra et al., 1997]. This paper analyzes the aurora borealis described by an eyewitness and the accompanying geophysical conditions in order to interpret it as a SAR arc.

GEOMAGNETIC CONDITIONS DURING THE AURORA BOREALIS IN IRKUTSK IN 1859

Review of the geomagnetic storms of August–September 1859 leads to the Carrington event, a complex of extreme events on the Sun and Earth, including the most powerful magnetic storm ever recorded. The geomagnetic storm started on September 2, 1859, according to the Gregorian calendar, which Russia began to use only in 1918. The difference between the old and new styles at that time was 12 days, so August 21, 1859 is September 2, 1859. Further, when discussing the 1859 aurora borealis in Irkutsk, we use the new style.

The 1859 geomagnetic storm actually consisted of two consecutive magnetic storms, which occurred on August 28 and September 2. The September 2 magnetic storm was caused by the Carrington—Hodgson white light solar flare that occurred on September 1 [Green et al., 2006].

The auroras seen during these days at their peak were described as bloody or dark crimson red, which were so bright that “you could read a newspaper”. The red auroras were classified as type A and lasted for several hours, reaching extremely low geomagnetic latitudes on August 28–29 (~25°) and September 2–3 (~18°). Auroras of all types and colors were observed below 50° N for ~24 hrs on August 28–29 and for ~42 hrs on September 2–3 [Green, Boardsen, 2006].

The minimum *Dst* index for this storm is estimated by experts from −900 to −1760 nT [Cliver, Dietrich, 2013], which is the maximum negative deviation in the history of magnetic observations. One of the possible sources of such a magnetic disturbance may be an amplified ring current [Tsurutani et al., 2003]. The magnetic storm main phase lasted for ~1.5 hrs, and the position of the plasmapause during the main phase was estimated by Lakhina and Tsurutani [2016] as L=1.3.

According to archival magnetic data from the Russian observation network, on September 2, 1859 between 04 and 06 UT a very strong short-term magnetic disturbance (t=1–2 hrs) began at all stations [Tyasto et al., 2009]. Between ~4:30 and 6:30 UT, the hourly values of the magnetic field H component sharply increased and exceeded the measurement scale at stations in St. Petersburg, Ekaterinburg, and Barnaul. The exception is the station in Nerchinsk. This time interval is probably correspond to the magnetic storm main phase.

Figure 1 presents a fragment of a figure from [Tyasto et al., 2009] with hourly values of deviations of the magnetic field H component from mean on September 1–5, 1859 for the stations Barnaul (53° N, 82° E) and Nerchinsk (51° N, 117°E). The red rectangle marks the time of observation of the aurora borealis in Irkutsk (52° N, 104° E, L~2). In longitude, Irkutsk is midway between Barnaul and Nerchinsk at latitudes close to them. Also shown is the time interval of crochet observation that is associated with a large flux of ionizing electromagnetic radiation during the Carrington solar flare (between 11 and 12 UT on September 1, 1859). According to Tyasto et al. [2009], the nature of H-component variations on September 2–3 indicates that during this storm there was an extreme increase in ionospheric and/or magnetospheric current at middle and high latitudes.

The above description of the 1859 aurora borealis in Irkutsk and its associated geomagnetic and ionospheric disturbances may coincide with the geophysical conditions and descriptions of characteristics and dynamics of SAR arcs, which have recently been observed with high-sensitivity equipment at the ISTP SB RAS Geophysical Observatory (GPhO) (52° N, 103° E) [Mikhalev et al., 2018]. Figure 2 exemplifies detection of SAR arcs in the 630.0 nm red oxygen line (the wavelength corresponds to the red range) by all-sky cameras at GPhO, located 100 km southwest of Irkutsk, as a bright stripe stretching across the entire sky from west to east near the zenith in the images, which is consistent with the eyewitness's description of the September 2, 1859 aurora.

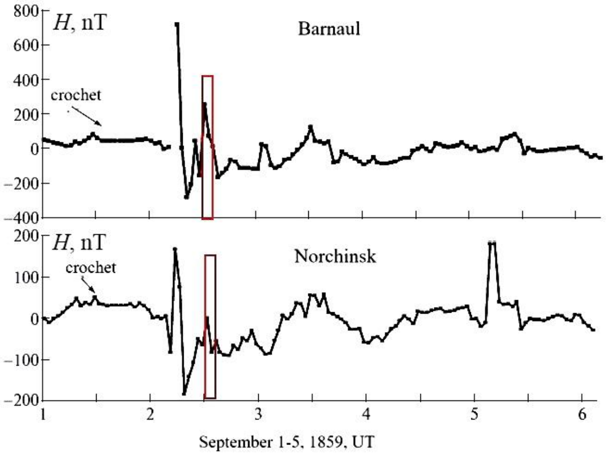

Figure 1. Hourly values of deviations of the magnetic field H component from mean on September 1–5, 1859 for the stations Barnaul and Nerchinsk [Tyasto et al., 2009] and the time interval of observation of the aurora borealis in Irkutsk [Chernigov, 2003] (marked with red rectangle)

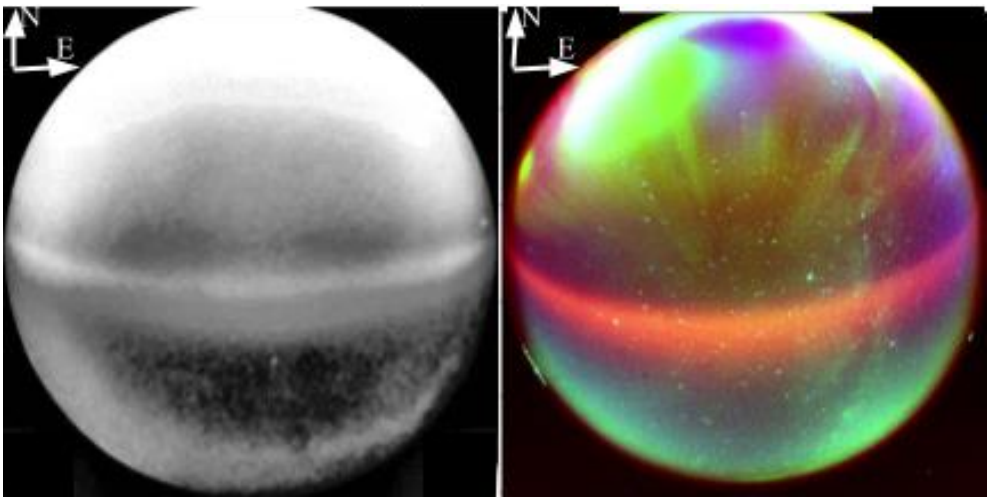

Figure 2. Images of SAR arcs observed at ISTP SB RAS GPhO during two magnetic storms on March 17, 2015 (*a*) and April 23, 2023 (*b*)

Figure 3 presents observational data on a SAR arc in the [OI] 630.0 nm emission, recorded by a zenith photometer during the recovery phase of the March 31, 2001 severe geomagnetic storm [Gorelyi et al., 2002; Degtyarev et al., 2003]. The formation of the SAR arc during the geomagnetic storm in 2001 under geophysical conditions similar to those of the storm in 1859 suggests that the arc in 1859 might have occurred during the magnetic storm recovery phase. This assumption is supported by the duration of the magnetic storm main phase from 04 to 06 UT (see above) and the time of observation of the SAR arc in Irkutsk from 12 to 15 UT.

Geomagnetic conditions on September 1–3, 1859 corresponding to the severe global geomagnetic storm [Tyasto et al., 2009], observations of various forms of auroras at middle and low latitudes [Green, Boardsen, 2006], description of the analyzed aurora in archival sources as a red arc across the entire sky, time and geomagnetic latitude of its observation, corresponding to L~2, — all this suggests that on September 2, 1859 the SAR arc was observed in Irkutsk during the recovery phase of the severe magnetic storm. Note that in [Hayakawa et al., 2018], a separate red aurora observed on September 1, 1859 at low latitudes (17–18° N) of the Western Hemisphere is also interpreted as a SAR arc. One of the reasons for this conclusion is the immobility of the red aurora for ~4–5 hours.

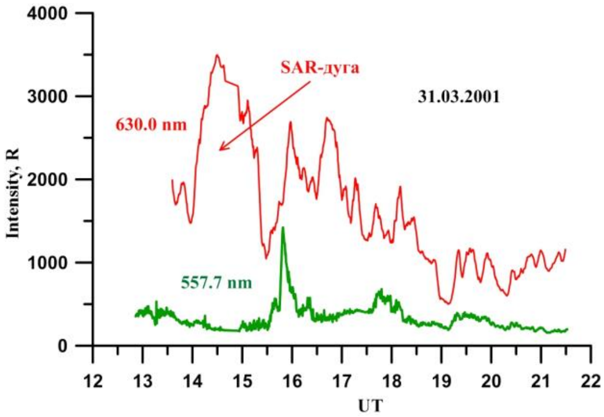

Figure 3. Variations in the intensity of [OI] 557.7 and 630.0 nm emissions on March 31, 2001 during the recovery phase of a strong magnetic storm. The data was obtained at ISTP SB RAS GPhO

LATITUDE LOCALIZATION OF SAR-ARCS AND GEOMAGNETIC ACTIVITY

Latitudinal distributions of SAR-arc observation rate during geomagnetic storms in the analyzed longitude sector are largely determined by the state of Earth's ring current and hence by variations in the *Dst* index [Ievenko, Alekseev, 2004]. A SAR arc is a projection of the plasmapause at ionospheric heights and reflects magnetospheric-ionospheric processes. The 630.0 nm emission of SAR arc is caused by a thermal energy flux from the magnetosphere to the thermosphere along the geomagnetic field, which occurs when a ring current amplified during a magnetic storm interacts with Earth's plasmasphere near the plasmapause [Baumgardner et al., 2008]; therefore, many authors attribute SAR arcs to the magnetospheric projection of the plasmapause onto the ionospheric F2-region [Rassoul et al., 1993].

As mentioned above, the location of the plasmapause during the main phase of the September 2–3, 1859 magnetic storm is estimated as L=1.3 [Lakhina, Tsurutani, 2016]. Irkutsk and GPhO have close corrected geomagnetic latitudes of ~47°, corresponding to L~2. It is therefore arguable that the magnetospheric projection of the plasmapause during the September 2–3, 1859 magnetic storm might have been in the sky over Irkutsk and crossed the zenith twice.

In turn, the plasmapause location in Earth's magnetosphere (L-shell) during geomagnetic storms depends on the magnitude of ring current (*Dst* index). Knowing the dependence of the L-shell on *Dst* during severe geomagnetic storms [Khorosheva, 2007], we can estimate the *Dst* index for the L-shell of the plasmapause. For the moment of SAR-arc observation at the zenith over Irkutsk (L~2) in 1859, *Dst* ranges from –300 to –400 nT. Unfortunately, due to the saturation effect of the L-shell dependence on the *Dst* index at L<2, the accuracy of such estimates is not high enough. On the other hand, there are more recent zenith observations of a SAR arc on March 31, 2001 near Irkutsk during the magnetic storm recovery phase at *Dst*~–300 nT [Degtyarev et al., 2003]. This SAR arc was observed simultaneously in two longitudinally spaced zones — south of Moscow at the IDG RAS station Mikhnevo and at GPhO in Tori village [Gorelyi et al., 2002]. The SAR-arc intensity was 3–4 kR at the station Mikhnevo and 2–3 kR near Irkutsk (GPhO). This makes the estimates of the *Dst* index (<–300 nT) more reliable during the observation of the SAR arc in Irkutsk in 1859.

SAR-ARC INTENSITY AND GEOMAGNETIC ACTIVITY

Unlike ordinary auroras observed during geomagnetic storms, SAR arcs in most cases have subvisual intensities (below the visual threshold in the red region ~10 kR). Only in very rare cases do SAR arcs have a brightness level that is visible with unaided eye [Lobzin, Pavlov, 1998; Baumgardner et al., 2008]. It should be emphasized that there is some inconsistency in the question about absolute SAR-arc intensities.

In [Hoch, 1973], it is observed that during the International Geophysical Year in 1957–1958 the typical SAR-arc intensity was ~1 kR with a maximum value of 10 kR recorded in 1958. Baumgardner et al. [2008] delve into the conditions for the occurrence of a SAR arc with an intensity of 13 kR on October 29, 1991. Finally, there is a report on a SAR arc with an intensity of 125 kR [Roach, Roach, 1963]. Rees and Akasofu [1963], using observations during high solar activity from 1956 to 1960, found positive correlations of the intensity of bright SAR arcs (300 R – 13 kR) with the geomagnetic indices *Dst* and K_p. At the same time, to bright SAR arcs with 11–13 kR intensities corresponded *Dst* ~ –210–220 nT. A linear approximation of the SAR-arc intensity dependence on *Dst*, according to the data from [Rees, Akasofu, 1963], yields a SAR arc intensity of 20 kR or higher with *Dst*~ –300 nT.

Given a fairly detailed description of the red arc in 1859 by the eyewitness, we can assume that its intensity exceeded the visual threshold in the red region ~10 kR. According to [Rees, Akasofu, 1963], at *Dst*~–300 nT or lower the maximum SAR-arc intensity can be 20 kR or higher. In both cases, the red arc observed in Irkutsk in 1859 can be attributed to intense SAR arcs.

It would be appropriate to mention the results obtained in [Zhang, 1985], which reported observations of the aurora borealis in Korea in 1507–1747 AD. Using the described characteristics of auroras and several statistical analyses, the author suggests that some of them were not ordinary auroras, but rather SAR arcs.

As discussed above, the September 2–3, 1859 magnetic storm features not only a record value of the *Dst* index, but also unusual optical manifestations [Green et al., 2006]. In this case, the SAR arc observed in Irkutsk in 1859 may expand the list of aurora types observed during this extreme geomagnetic storm and augment the list of the most intense SAR arcs.

CONCLUSIONS

Analysis of geomagnetic conditions on September 1–3, 1859 during the Carrington event, visual observations of auroras of various forms at middle and low latitudes during these days, as well as current ideas about the morphology and mechanisms of formation of SAR arcs, and comparison with instrumental observations of SAR arcs near Irkutsk allow us to assume that the red arc visually observed in Irkutsk on September 2, 1859 and described in the chronicles [Chernigov, 2003] is a SAR arc.

In this case, the SAR arc observed in Irkutsk on September 2, 1859 can augment the list of the most intense SAR arcs. The intensity of the SAR arc in 1859, described in the Irkutsk chronicles, can be estimated at ~10–20 kR.

From archival data from the Russian network of magnetic observations, we have determined that the SAR arc occurred during the recovery phase of the September 2, 1859 magnetic superstorm.

The projection of the plasmapause onto the ionosphere on September 2, 1859 at ~12 UT was at the latitude of Irkutsk.

The *Dst* value at ~12 UT on September 2, 1859 can be estimated from –300 to –400 nT.

We can concede that at the moment the above description of the September 2, 1859 aurora borealis in Irkutsk is the first substantive description of the SAR arc, a century before its discovery as a phenomenon [Barbier, 1958]. There is no doubt that humanity has repeatedly observed this phenomenon at midlatitudes in previous centuries.

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REFERENCES

Barbier D. Recherches sur la raie 630.0 de la luminescence atmospherique nocturne. *Ann. Geophys.* 1959, vol. 15, no. 2, pp. 179–217.

Baumgardner J., Wroten J., Semeter J., Kozyra J., Buonsanto M., Erickson P., Mendillo M. A very bright SAR arc: implications for extreme magnetosphere-ionosphere coupling. *Ann. Geophys*. 2008, vol. 25 (12), pp. 2593–2608.

Berrilli F., Giovannelli L. The great aurora of 4 February 1872 observed by Angelo Secchi in Rome. *J. Space Weather Space Climate.* 2022, vol. 12, 3. DOI: 10.48550/arXiv.2201.01171.

Chernigov A.K. *Irkutskie povestvovaniya. 1661–1917 gody* [Irkutsk Narrations. Years 1661–1917]. Irkutsk, Ottisk Publ., 2003, vol. 2, p. 188. (In Russian).

Cliver E.W., Dietrich W.F. The 1859 space weather event revisited: limits of extreme activity. *J. Space Weather Space Climate*. 2013, vol. 3, no. A31. DOI: 10.1051/swsc/2013053.

Degtyarev V.I., Mikhalev A.V., Jiyao Xu. Variations of night airglow in Eastern Siberia during the magnetic storm on March 31 – April 4, 2001. *Optika atmosfery i okeana* [Atmospheric and Oceanic Optics]. 2003, vol. 16, no. 5-6, pp. 552–556. (In Russian).

Gorelyi K.I., Karachiev V.D., Ievenko I.B., Alekseev V.N., Mikhalev A.V., Beletskii A.B. Simultaneous optical observations of the strong magnetic storm on March 31, 2001 in Moscow, Eastern Siberia, and Yakutia. *Solar-Terrestrial Physics*. 2002. Vol. 2 (115). P. 265–266. (In Russian).

Green J.L., Boardsen S. Duration and extent of the great auroral storm of 1859. *Adv. Space Res.* 2006, vol. 38, pp. 130–135.

Green J.L., Boardsen S., Odenwald S., Humble J., Pazamickas K.A. Eyewitness reports of the great auroral storm of 1859. *Adv. Space Res.* 2006, vol. 38, pp. 145–154. DOI: 10.1016/j.asr.2005.12.021.

Hayakawa H., Ebihara Y., Hand D.P., Hayakawa S., Kumar S., Mukherjee S., Veenadhari B. Low-latitude aurorae during the extreme space weather events in 1859. *Astrophys. J.* 2018, vol. 869, no. 1. DOI: 10.3847/1538-4357/aae47c.

Hoch R.J. Stable auroral red arcs. *Rev. Geophys. Space Phys*. 1973, vol. 11, pp. 935–949.

Iyevenko I.B., Alekseyev V.N. Substorm and storm effect on a SAR arc dynamics. Statistical analysis. *Geomagnetizm i aeronomiya* [Geomagnetism and aeronomy]. 2004, vol. 44, no. 5, pp. 643–654. (In Russian).

Kataoka R., Uchino S., Fujiwara Y., Fujita S., Yamamoto K. Fan-shaped aurora as seen from Japan during a great magnetic storm on February 11, 1958. *J. Space Weather Space Climate*. 2019, vol. 9, no. A16. DOI: 10.1051/swsc/2019013.

Knipp D.J., Bernstein V., Wahl K., Hayakawa H. Timelines as a tool for learning about space weather storms. *J. Space Weather Space Climate*. 2021, vol. 11, no. 29. DOI: 10.1051/ swsc/2021011.

Khorosheva O.V. Correlation between geomagnetic disturbances and the magnetosphere dynamics and interplanetary space parameters *Geomagnetizm i aeronomiya* [Geomagnetism and aeronomy]. 2007, vol. 47, no. 5, pp. 579–583. (In Russian).

Kozyra J.U., Nagy A.F., Slater D.W. High-altitude energy source(s) for stable auroral red arcs. *Rev. Geophys.* 1997, vol. 35, iss. 2, pp. 155–190. DOI: 10.1029/96RG03194.

Lakhina G.S., Tsurutani B.T. Geomagnetic storms: historical perspective to modern view. *Geosci. Let*. 2016, vol. 3, iss. 1. DOI: 10.1186/s40562-016-0037-4.

Lobzin V.V., Pavlov A.V. Correlation of the glow of subauroral red arcs with solar and geomagnetic activities. *Geomagnetizm i aeronomiya* [Geomagnetism and aeronomy]. 1998, vol. 38, no. 4, pp. 49–61. (In Russian).

Mikhalev A.V., Beletsky A.B., Vasilyev R.V., Zhereb-tsov G.A., Podlesny S.V., Tashchilin M.A., Artamonov M.F. Spectral and photometric characteristics of mid-latitude auroras during the magnetic storm of March 17, 2015. *Solar-Terr. Phys.* 2018, vol. 4, no. 4, pp. 42–47. DOI: 10.12737/stp-44201806.

Rassoul H.K., Rohrbaugh R.P., Tinsley B.A., Slater D.W. Spectrometric and photometric observations of low-latitude aurorae. *J. Geophys. Res.* 1993, vol. 98, no. A5, pp. 7695–7709.

Rees M.H., Akasofu S.I. On the association between subvisual red arcs and the *Dst* (H) decrease. *Planet. Space Sci*. 1963, vol. 11, no. 2, pp. 105–107.

Roach F.E., Roach J.R. Stable 6300 Å auroral arcs in midlatitudes. *Planet. Space Sci*. 1963, vol. 11, iss. 5, pp. 523–545.DOI: 10.1016/0032-0633(63)90076-x.

Tsurutani B.T., Gonzalez W.D., Lakhina G.S., Alex S. The extreme magnetic storm of 1–2 September 1859. *J. Geophys. Res.: Space Phys*. 2003, vol. 108, no. A7. DOI: 10.1029/2002JA009504.

Tyasto M.I., Ptitsyna N.G., Veselovskiy I.S., Yakovchuk O.S. The extreme magnetic storm of September 2–3, 1859 from archive magnetic data of Russian observational network. *Geomagnetizm i aeronomiya* [Geomagnetism and aeronomy]. 2009, vol. 49, no. 2, pp. 163–173. (In Russian).

Zhang Z. Korean auroral records of the period AD 1507–1747 and the SAR arcs. *J. Brit. Astron. Assoc*. 1985, vol. 95, iss. 5, pp. 205–210.

URL: http://ckp-angara.iszf.irk.ru (accessed November 8, 2024).

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