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Two opposite processes in atmospheric GCR ionization − compensation between SEP and Forbush effects during simultaneous action of solar and geomagnetic storms

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Abstract

High-energy particles of cosmic origin e.g. cosmic ray protons and heavier nuclei of galactic and/or solar origin induce complicated nuclear-electromagnetic-meson cascades in the Earth's atmosphere, eventually leading to an ionization of the ambient air. The induced by cosmic rays atmospheric ionization is related to possible effect of precipitating particles on atmospheric physics and chemistry. These effects can be considerably enhanced during strong and moderately strong solar proton events. While the contribution of galactic cosmic ray particles to ion production in the atmosphere is slightly variable throughout a solar cycle, relativistic solar particles could produce a significant excess on ion pair production, particularly over polar caps. This effect is strong on a short time scales. On the other hand, depressions of the galactic cosmic ray flux, that is, Forbush decreases, can significantly impact the galactic cosmic ray induced ionization. The sequence of three ground level enhancements observed in October-November 2003, specifically the second: GLE 66 occurred during a giant Forbush decrease, provides unique opportunity to study impact ionization on extended time scale, explicitly considering the reduced galactic cosmic ray flux. Using Monte Carlo simulations we computed ion production rate and corresponding ionization effect in the atmosphere during GLE 66 occurred on 29.10.2003 – the biggest storm (29 – 31.10.) since 32 years, explicitly considering the Forbush decrease and the complex geomagnetospheric conditions.

Абстракт

Високо-енергетични частици с космически произход, т.е. протони и по-тежки ядра на космическите лъчи от галактически и/или слънчев произход индуцират сложни ядрено-електромагнитно-мезонни каскади в Земната атмосфера, като евентуално предизвикват йонизация на въздуха в нея. Индуцираната от космическите лъчи атмосферна йонизация е свързана с възможния ефект от изсипващи се частици в атмосфернага физика и химия. Тези ефекти могат да бъдат значително усилени през време на силни и умерено силни слънчеви протонни събития. Докато приносът на частиците от галактическите космически лъчи за йонната продукция в атмосферата е слабо променлив по време на слънчевия цикъл, релативистките слънчеви частици могат да предизвикат значителено увеличение на продукцията на електрон – йонни двойки, особено над полярните шапки. Този ефект е силен за къси времеви интервали. От друга страна, спадът на потока на галактическите космически лъчи, т.е. Форбуш намаленията, могат значително да повлияят върху йонизацията, индуцирана от галактическите космически лъчи. Последователността от три увеличения на земната повърхност, наблюдавани през Октомври – Ноември 2003 , особено второто – GLE 66, възникнало през време на гигантско Форбуш – намаление, дава единствена възможност за изучаване на влиянието върху йонизацията в по-широк времеви интервал, по-точно като се разглежда спада в потока на галактическите космически лъчи. Като използваме Монте Карло симулация, ние изчисляваме скоростта на йонната продукция и съответния йонизационен ефект в атмосферата през време на GLE 66, възникнал на 29 Октомври 2003, като разглеждаме Форбуш намалението и комплексните геомагнетосферни условия през време на най-силната магнитна буря (29 – 31.10.) от 32 години.

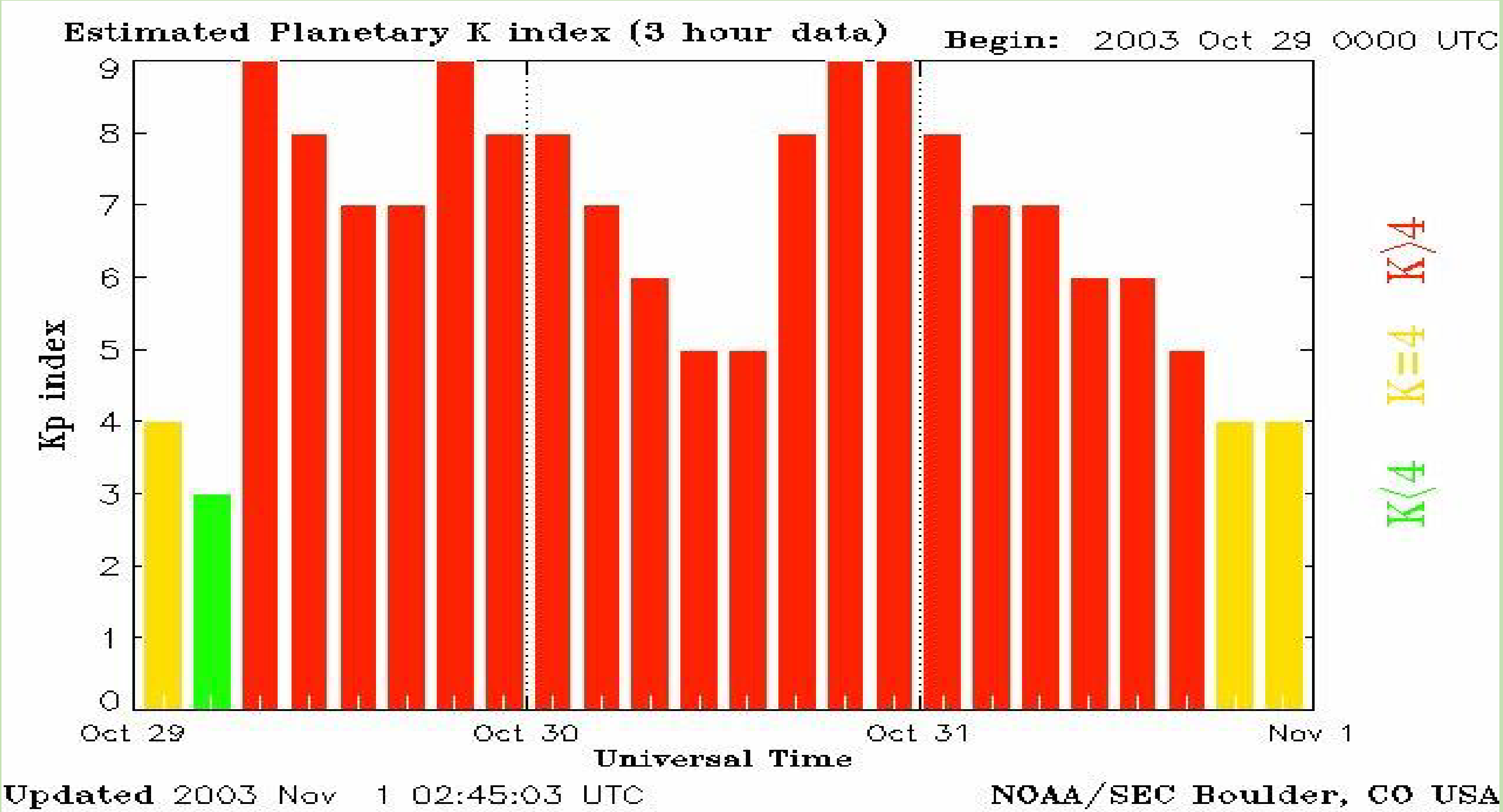

Fig. 1. The Kp index during October 29-31, 2003. Kp values of 9 were observed on October 29 and 30. This indicates severe storm events for extended periods on both days. Aurora were observed at mid-latitudes in the United States. Development of strong SED (Storm Enhanced Density) was also observed in North America.

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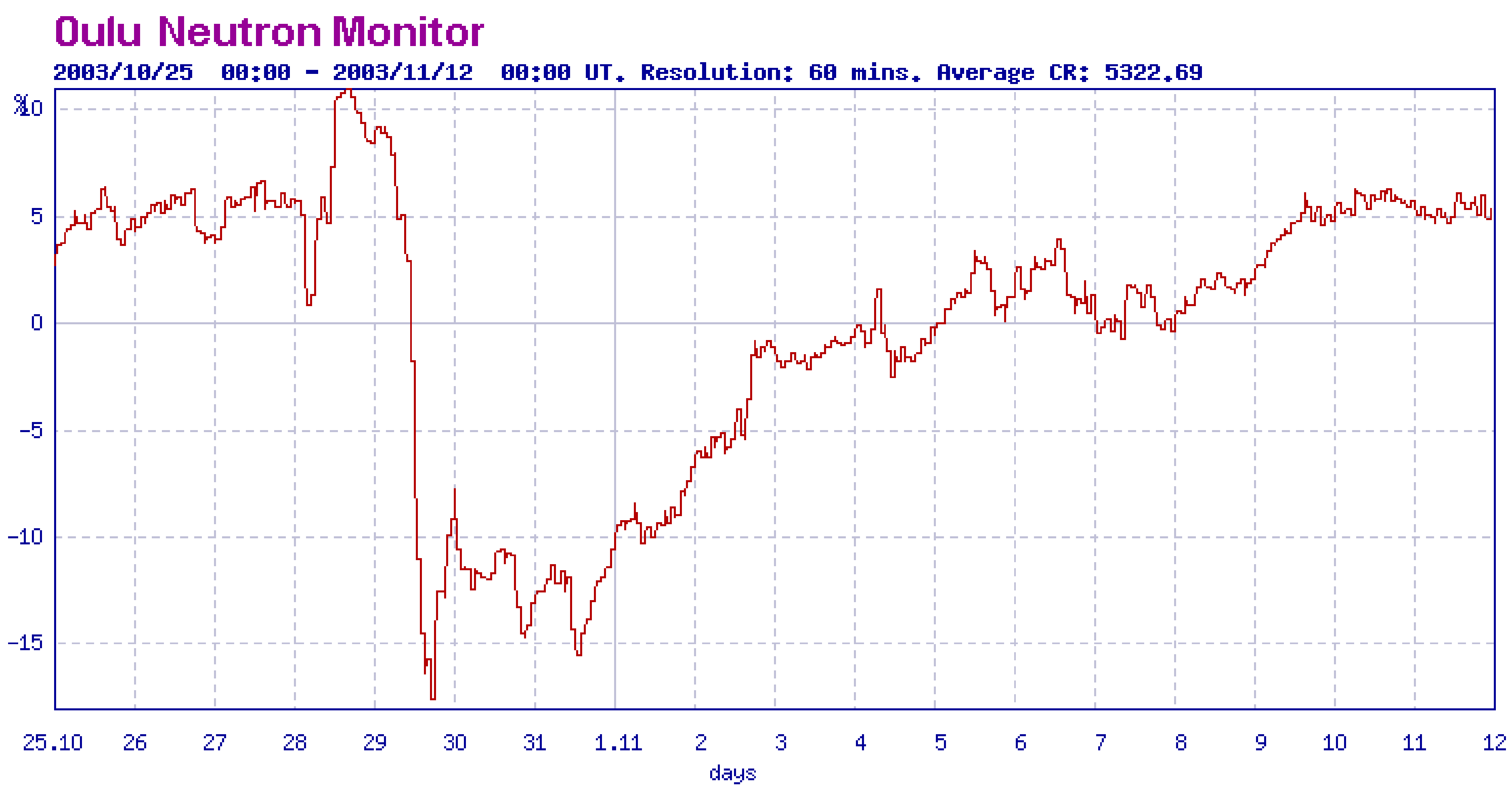


Fig. 2. Count rate variation of Oulu neutron monitor (effective vertical cutoff rigidity Rc =0.81 GV) during October 25-November 12, 2003. One can see the deep nearly 12-day lasting Forbush decreases from 29 October to 10 November, 2003. It is visible also the three-step Forbush effect on October 29-31 (maximum effect), corresponding to the three-step geomagnetic superstorm on Fig. 1.

Local interstellar spectrum

$$j_{\mathrm{LIS}} = 2.70\,\frac{E^{1.12}}{\beta^2}\left(\frac{E+0.67}{1.67}\right)^{-3.93}$$

where E is the kinetic energy in GeV, β is ratio of particle speed relative to the speed of light , and $j_{\mathrm{LIS}} = P^2\, f$ is the differential intensity given in units of particles $m^{-2}s^{-1}sr^{-1}\,MeV^{-1}$ with P as the rigidity in GV and f as the GCR distribution function. The very LIS – local interstellar spectrum, is specified at the heliopause HP taken at 122 AU, according data of AIS Voyager 1.

The very LIS – local interstellar spectrum is computed and it is shown first in the paper:

Etienne E. Vos and Marius S. Potgieter. New modeling of galactic proton modulation during the minimum of solar cycle 23/24. The Astrophysical Journal, 2015, December 20, 815:119 (8pp)
2015. The American Astronomical Society

A series of publications is dedicated recently to that scientific field.

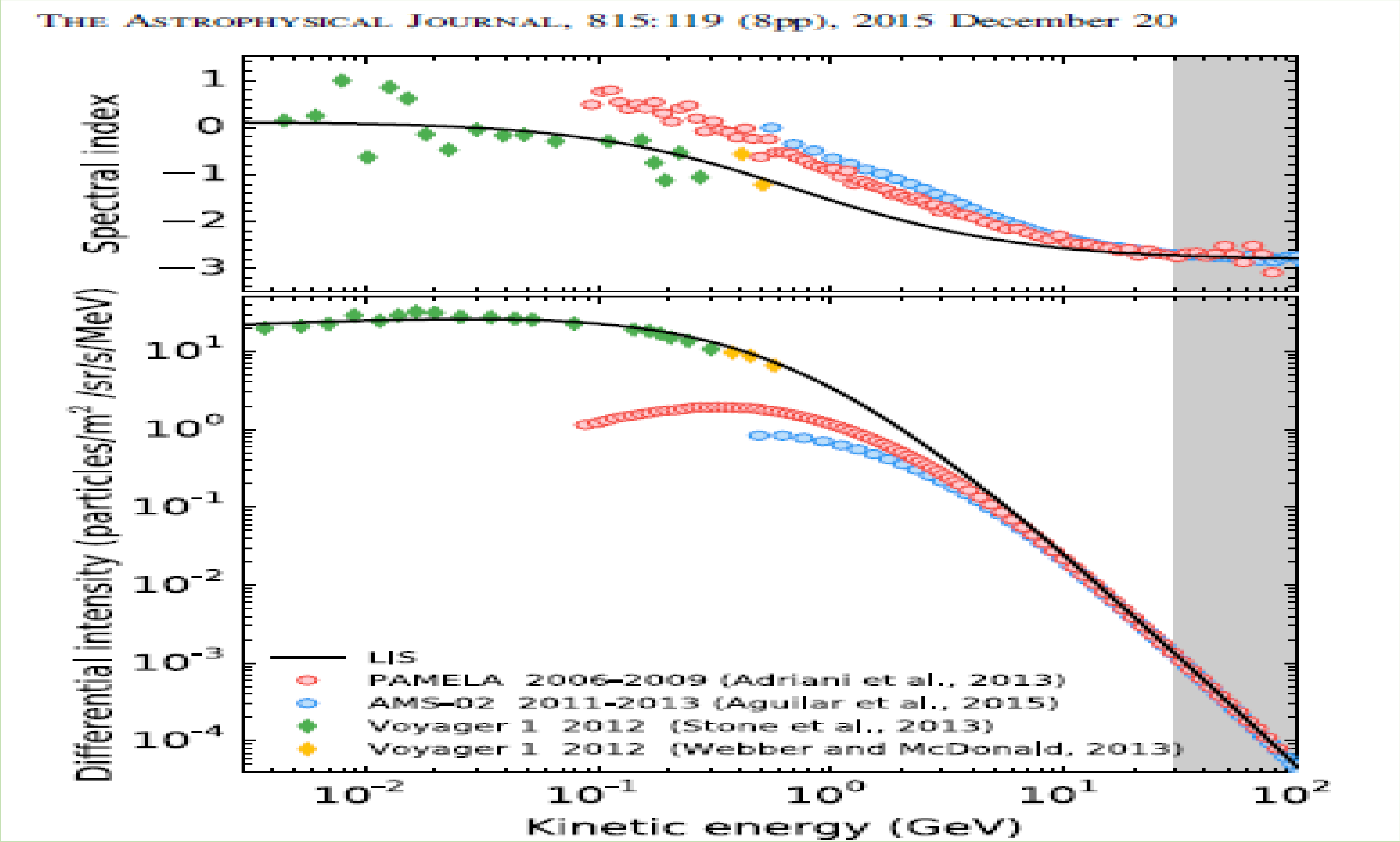
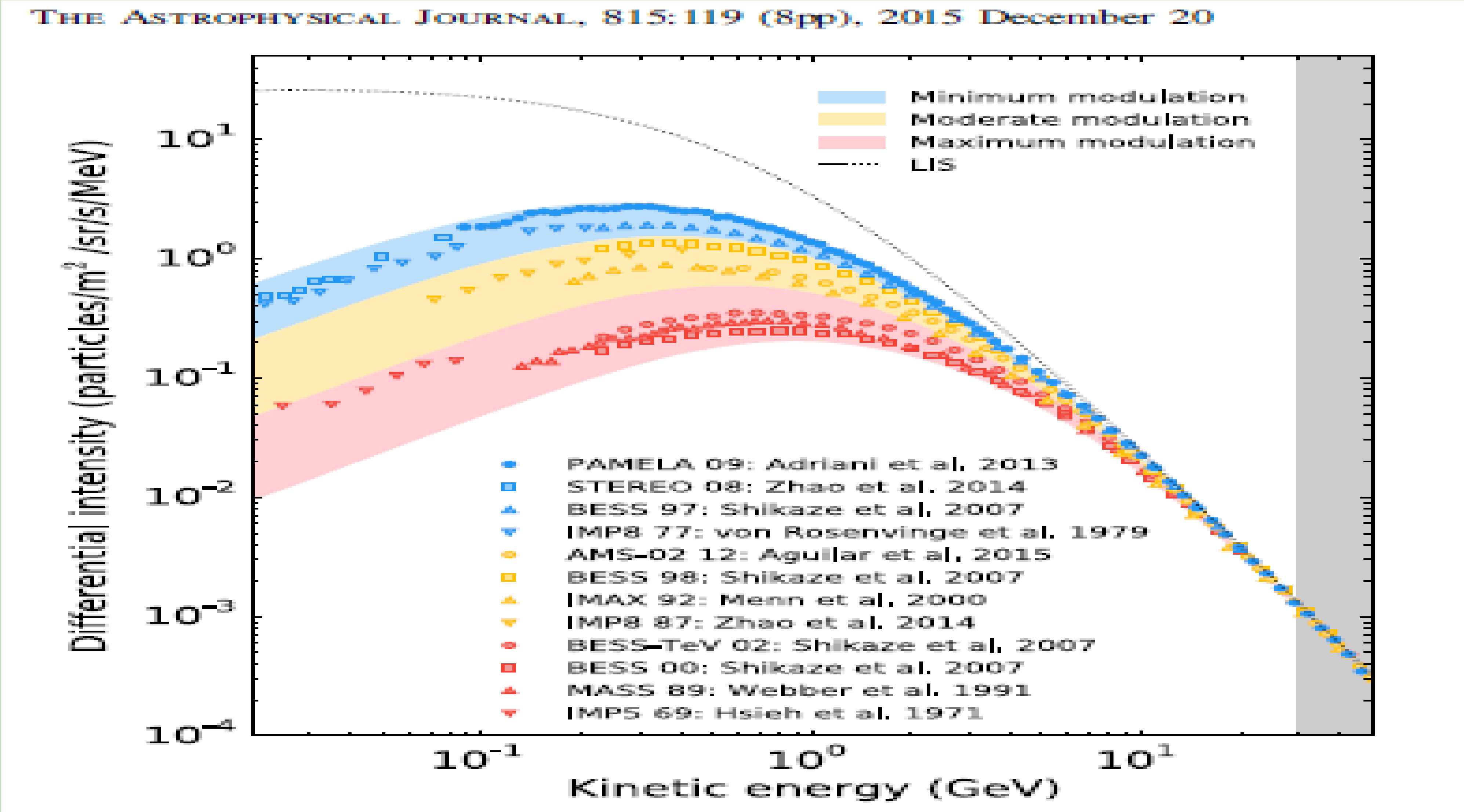

The Astrophysical Journal, 815:119 (8pp), 2015 December 20
Spectral index
Differential intensity (particles/m² /sr/s/MeV)
Kinetic energy (GeV)
LIS
PAMELA 2006–2009 (Adriani et al., 2013)
AMS–02 2011–2013 (Aguilar et al., 2015)
Voyager 1 2012 (Stone et al., 2013)
Voyager 1 2012 (Webber and McDonald, 2013)

Figure 3.

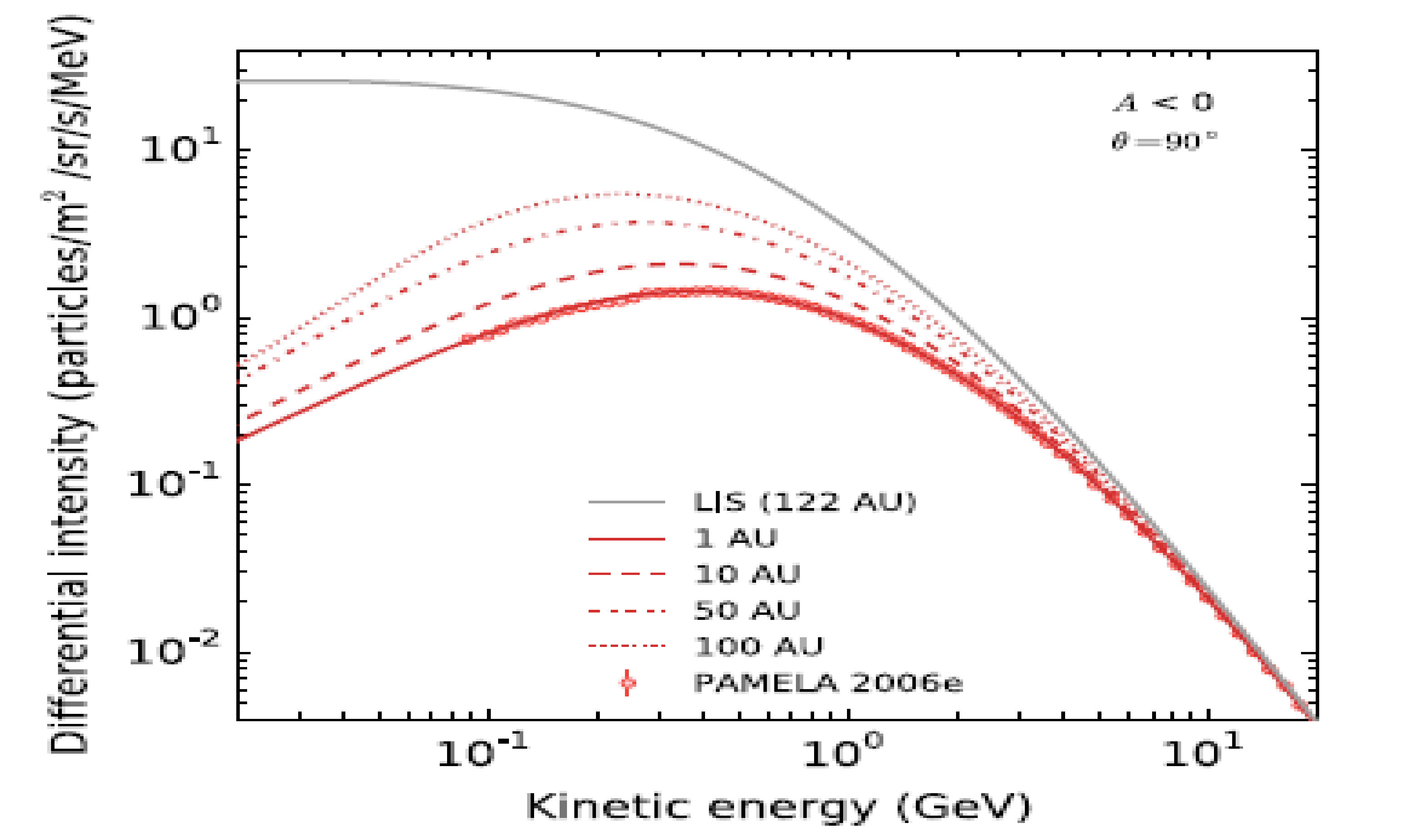
Figure. 3. Newly constructed proton very LIS used in this study (black line). *PAMELA*, *AMS-02*, and *Voyager 1* observations (colored symbols) were used to obtain this very LIS. Differential intensity is given in the bottom panel with the corresponding spectral index shown in the top panel. The very LIS is normalized to observations above 30 GeV (grey band).



THE ASTROPHYSICAL JOURNAL, 815:119 (8pp), 2015 December 20
Minimum modulation
Moderate modulation
Maximum modulation
LIS
PAMELA 09: Adriani et al. 2013
STEREO 08: Zhao et al. 2014
BESS 97: Shikaze et al. 2007
IMP8 77: von Rosenvinge et al. 1979
AMS-02 12: Aguilar et al. 2015
BESS 98: Shikaze et al. 2007
IMAX 92: Menn et al. 2000
IMP8 87: Zhao et al. 2014
BESS-TeV 02: Shikaze et al. 2007
BESS 00: Shikaze et al. 2007
MASS 89: Webber et al. 1991
IMP5 69: Hsieh et al. 1971
Differential intensity (particles/m² /sr/s/MeV)
Kinetic energy (GeV)

Figure 4.

Figure 4. Proton spectrum measured by *PAMELA* at the end of 2009 (solid blue circles), recognized as being the highest spectrum ever recorded at the Earth, is compared to spectra from other experiments at different times in the solar cycle. Blue, orange, and red bands show approximate regimes for minimum, moderate, and maximum heliospheric modulation, respectively. The grey band is where modulation is considered negligible.



Differential intensity (particles/m² /sr/s/MeV)
10¹
10⁰
10⁻¹
10⁻²
A < 0
θ = 90°
LIS (122 AU)
1 AU
10 AU
50 AU
100 AU
PAMELA 2006e
10⁻¹
10⁰
10¹
Kinetic energy (GeV)

Figure 5.

Figure 5. Reproduced and observed *PAMELA* 2006e spectrum, used as a reference spectrum for the development of the solar minimum up to the end of 2009. Computed spectra at 1, 10, 50, and 100 AU are given by the solid, dashed, dashed - dotted, and dotted lines, respectively, in the equatorial plane (i. e., $\Theta = 90^{\circ}$). The LIS from Figure 8 (grey line) is specified at 122 AU.

Newly constructed proton very LIS used in this study is obtained from PAMELA, AMS-02 and Voyager 1 observations. The differential intensity and the corresponding spectral index are normalized to the measurements from PAMELA, AMS-02 and Voyager 1 detectors. Voyager 1 is automatic spacecraft which investigated the external parts of the Solar system. It is launched on 5 September 1977 and towards 2021 it functionates although with reduced opportunities. It visited also Jupiter and Saturn. Until recently, every spacecraft in history had made all of its measurements inside our heliosphere, the magnetic bubble inflated by our Sun. But on Aug. 25, 2012, NASA's Voyager 1 changed that. As it crossed the heliosphere's boundary, it became the first human-made object to enter – and measure – interstellar space. Now nine years into its interstellar journey, a close listen of Voyager 1's data is yielding new insights into what that frontier is like.

Electron production rate

$$q(h) = \frac{1}{Q} \sum_{i} \int_{E_i}^{\infty} \int_{\varphi=0}^{2\pi} \int_{\Theta=0}^{\frac{\pi}{2}} D_i(E,h) \left[\frac{dE}{dh}(h)\right]_i \sin\Theta d\Theta d\varphi dE$$

q(h) – electron production rate at height *h*, *Q* = 35 eV – energy for production of one electron – ion pair, E_i – energy corresponding to the geomagnetic threshold of particle *i* , $D_i(E,h)$ - differential spectrum of particle *i* , $\left[\frac{dE}{dh}(h)\right]_i$ - ionization losses ~ yield function, *Θ*- penetration angle towards the vertical, φ - horizontal angle of particle penetration, *E* – total particle energy.

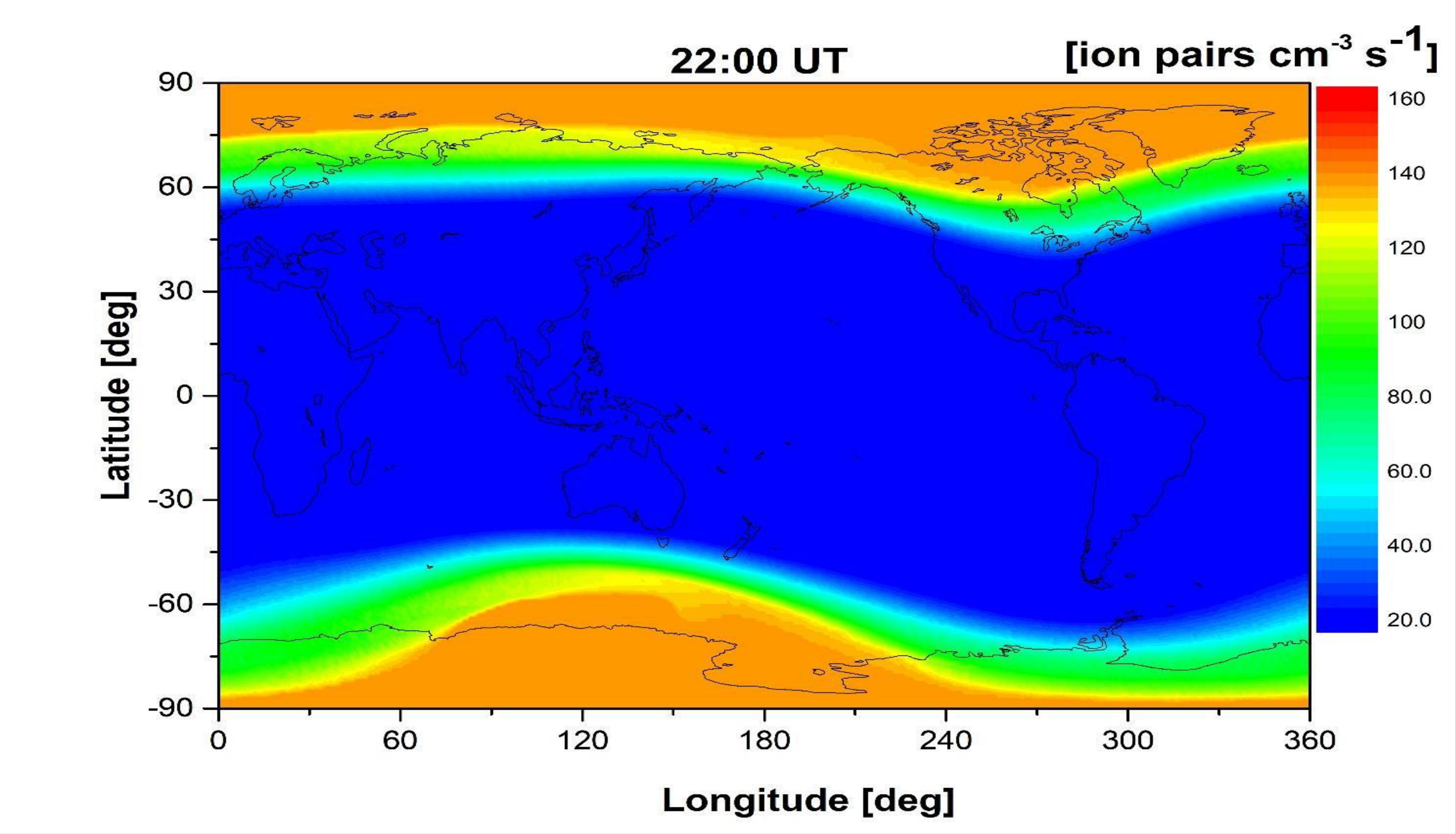
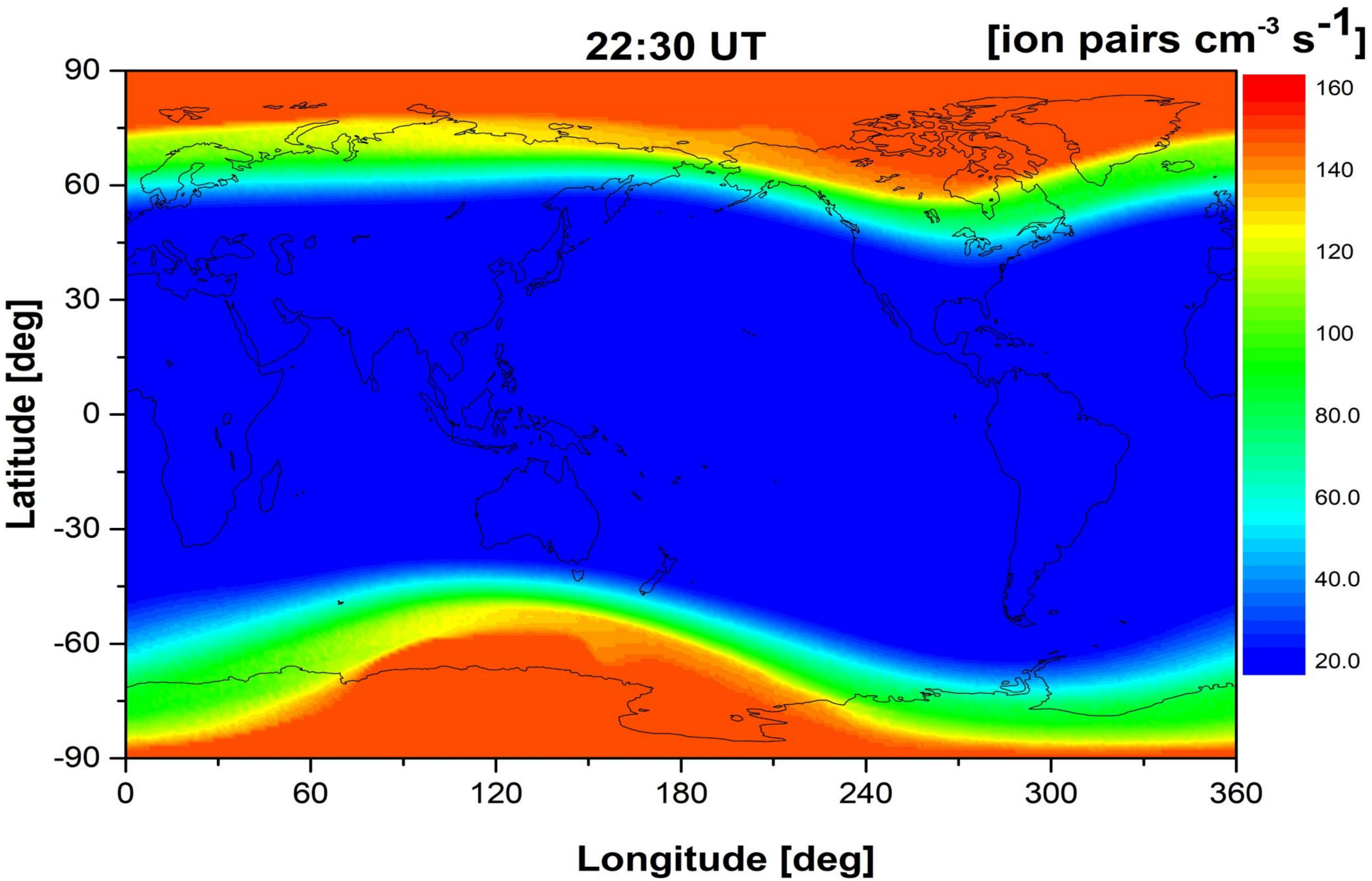
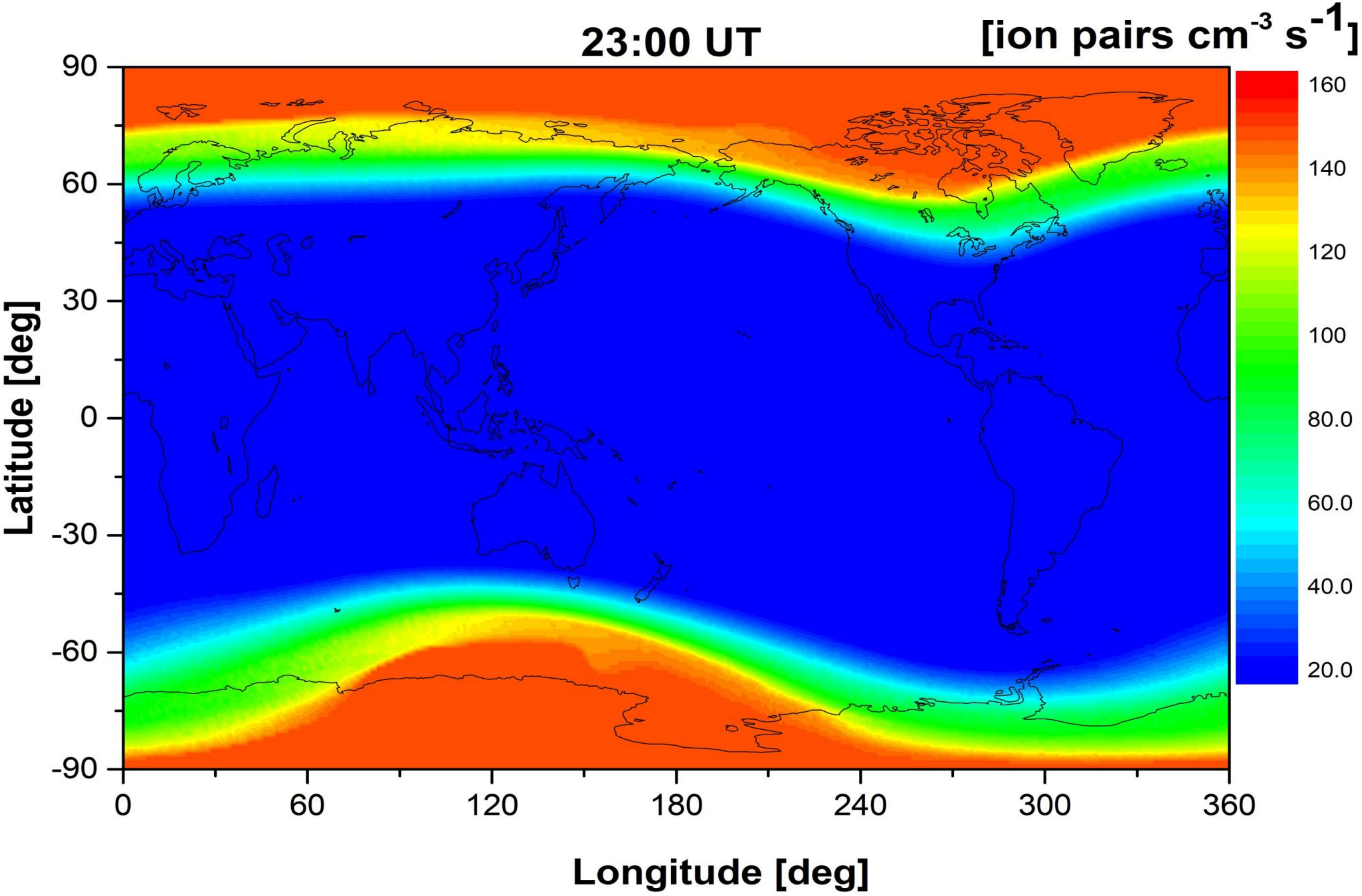
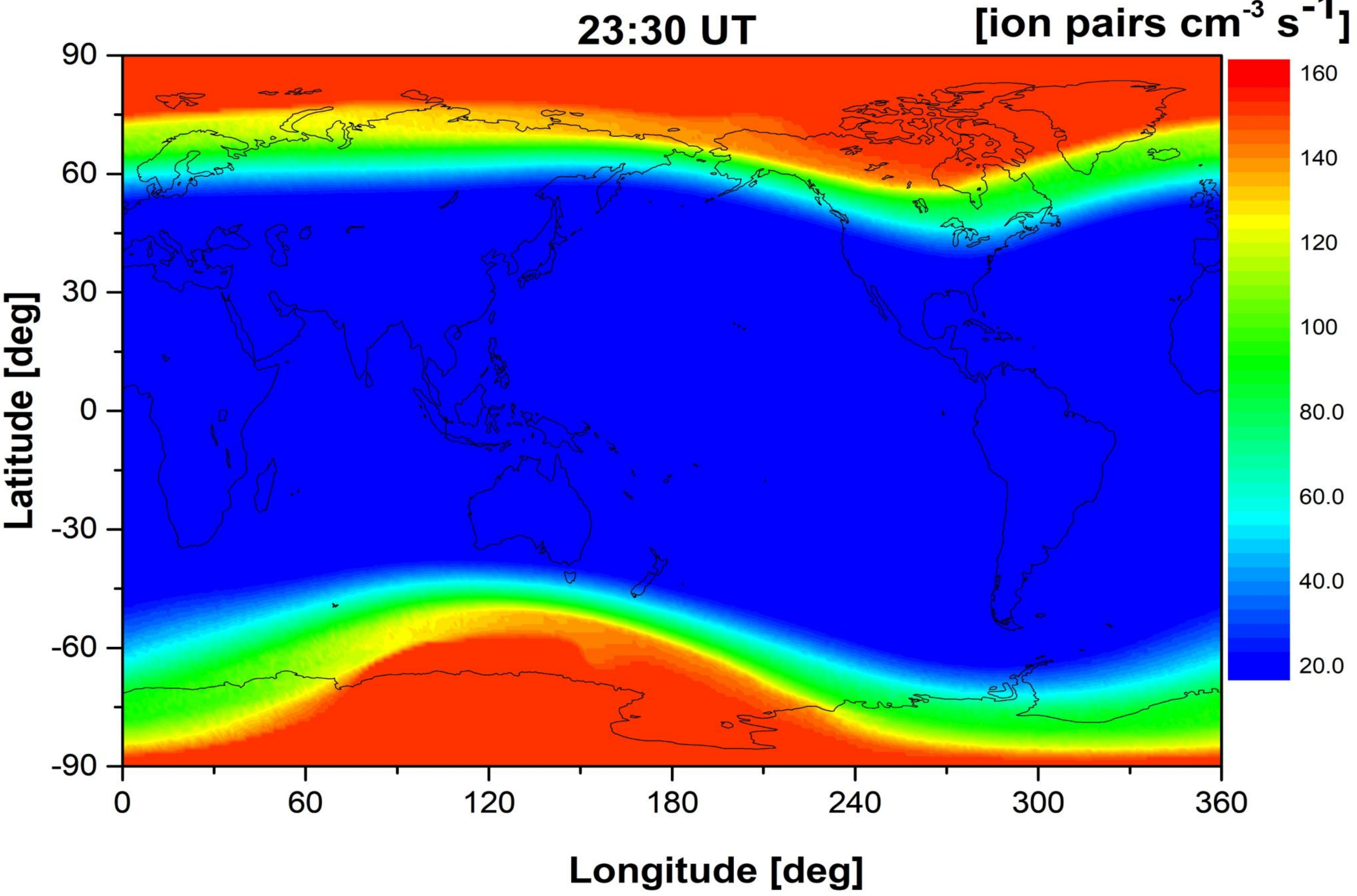


Fig. 6 a,b,c,d. Global map of ion production rate in the region of Regener-Pfotzer maximum due to CRs of galactic and solar origin during the initial phase (22:00 UT) of GLE 66 on 29 October 2003; and after that on Fig. 6. b, c, d.


22:30 UT
[ion pairs cm-3 s-1]
Latitude [deg]
Longitude [deg]
90
60
30
0
-30
-60
-90
0
60
120
180
240
300
360
160
140
120
100
80.0
60.0
40.0
20.0


23:00 UT
[ion pairs cm^{-3} s^{-1}]
160
140
120
100
80.0
60.0
40.0
20.0
90
60
30
0
-30
-60
-90
Latitude [deg]
0
60
120
180
240
300
360
Longitude [deg]


23:30 UT
[ion pairs cm^{-3} s^{-1}]
Latitude [deg]
Longitude [deg]
90
60
30
0
-30
-60
-90
0
60
120
180
240
300
360
160
140
120
100
80.0
60.0
40.0
20.0

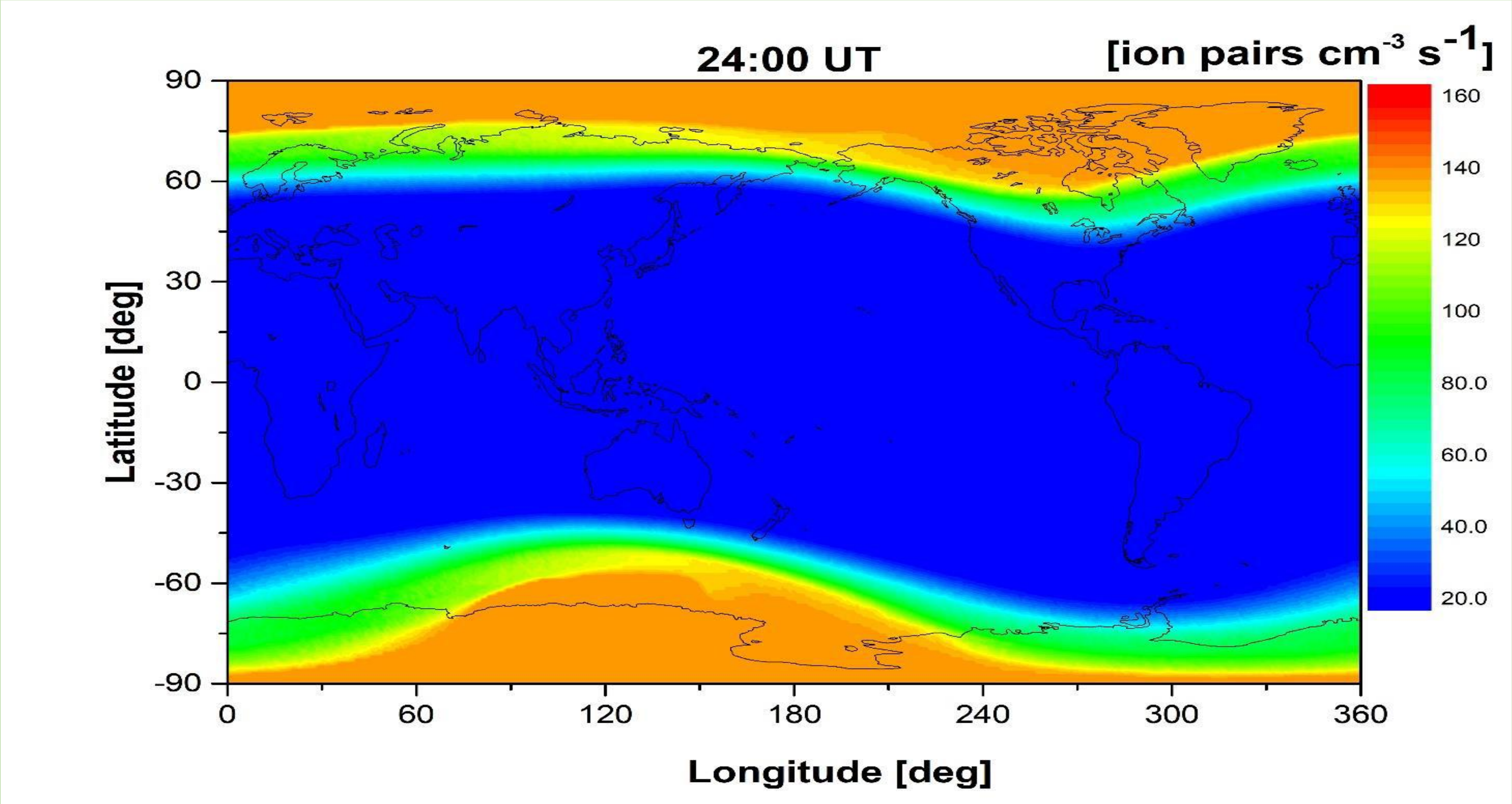


Fig. 7. Global map of ion production rate in the region of Regener-Pfotzer maximum due to CRs of galactic and solar origin during the late phase (24:00 UT) of GLE 66 on 29 October 2003.

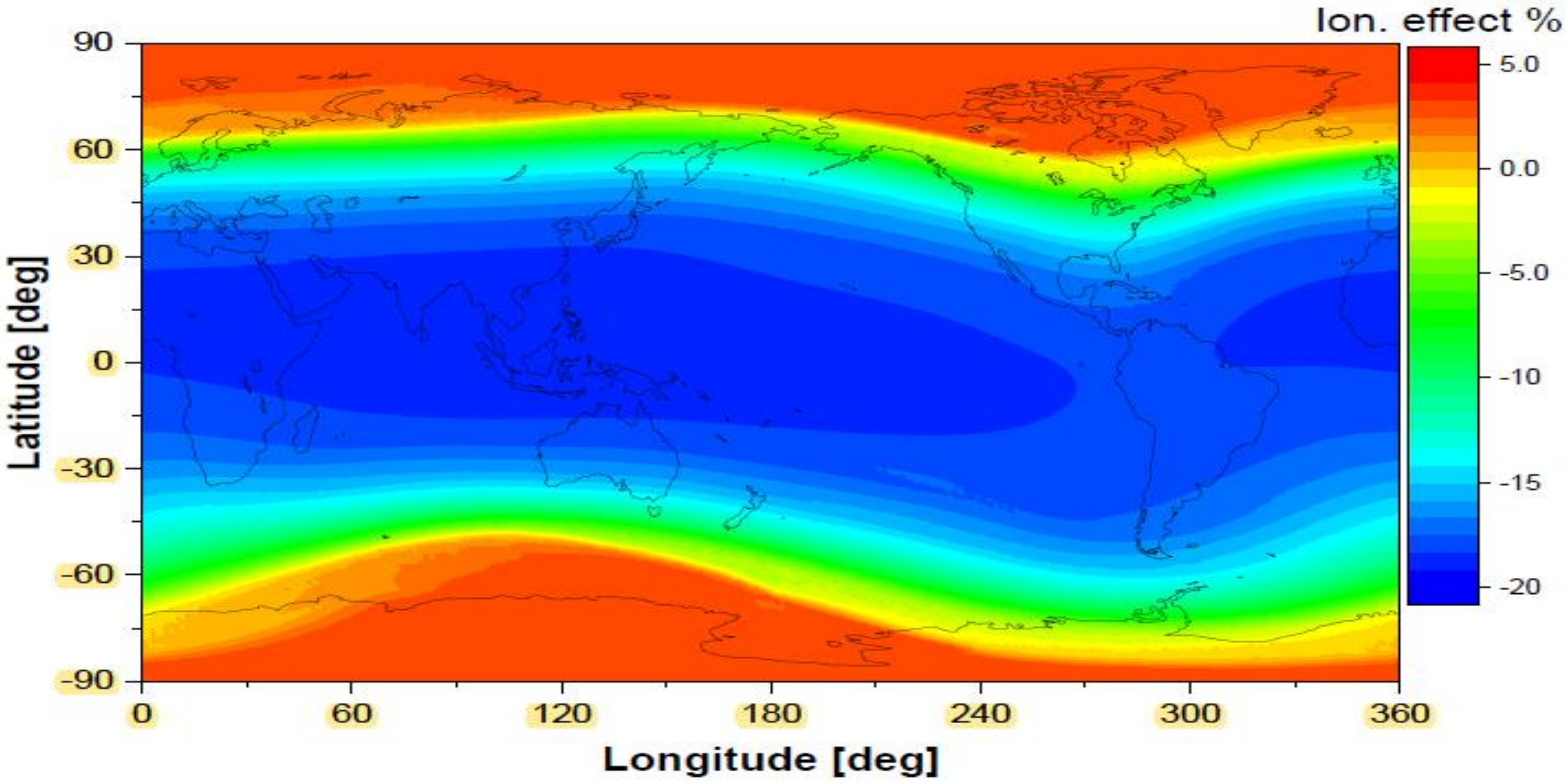


Fig. 8. Global map of 24h averaged ionization effect in the region of Regener-Pfotzer maximum due to CRs of galactic and solar origin during the GLE 66 on 29 October2003.

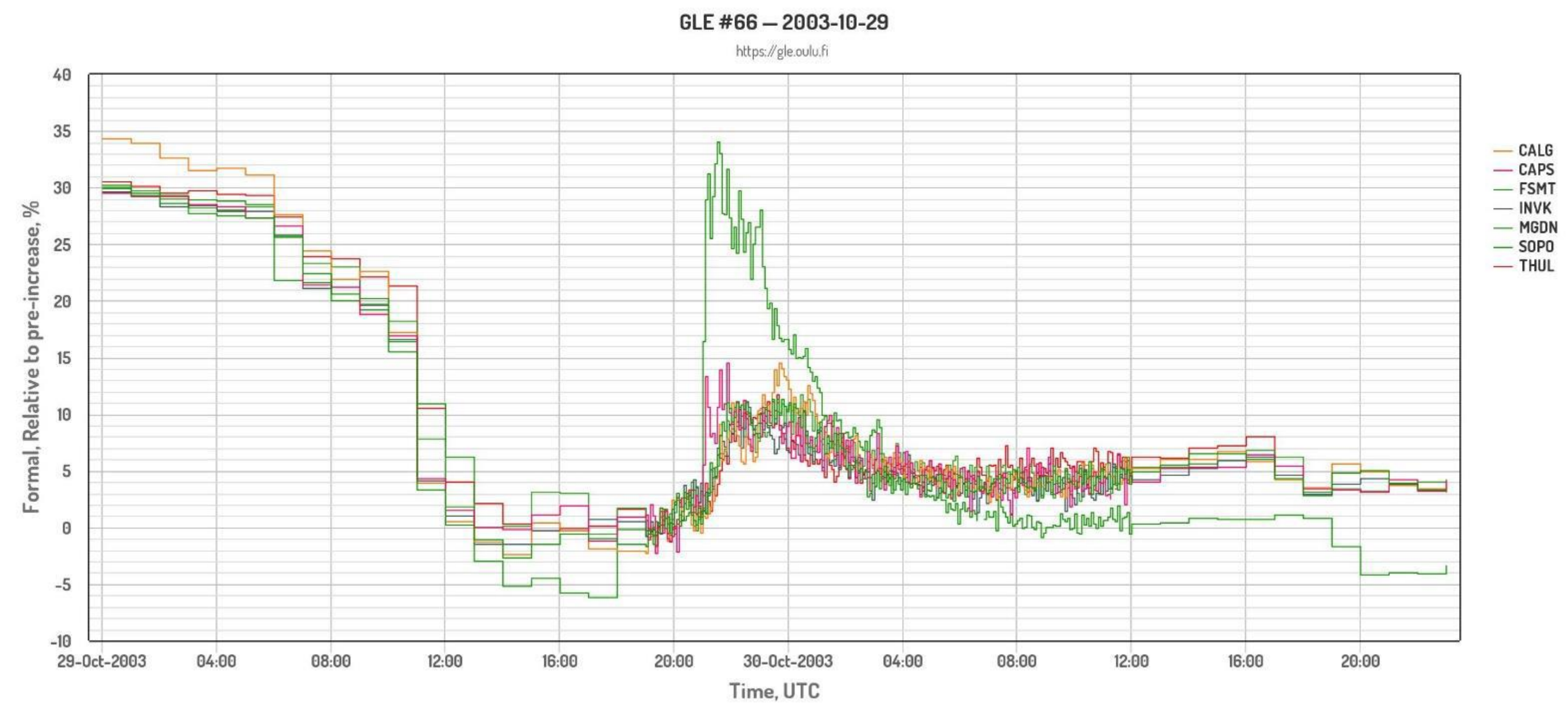


Fig. 9. Count rate time variations of selected neutron monitor stations during GLE 66 on 29 October 2003. The Forbush decrease is clearly seen before the event onset.

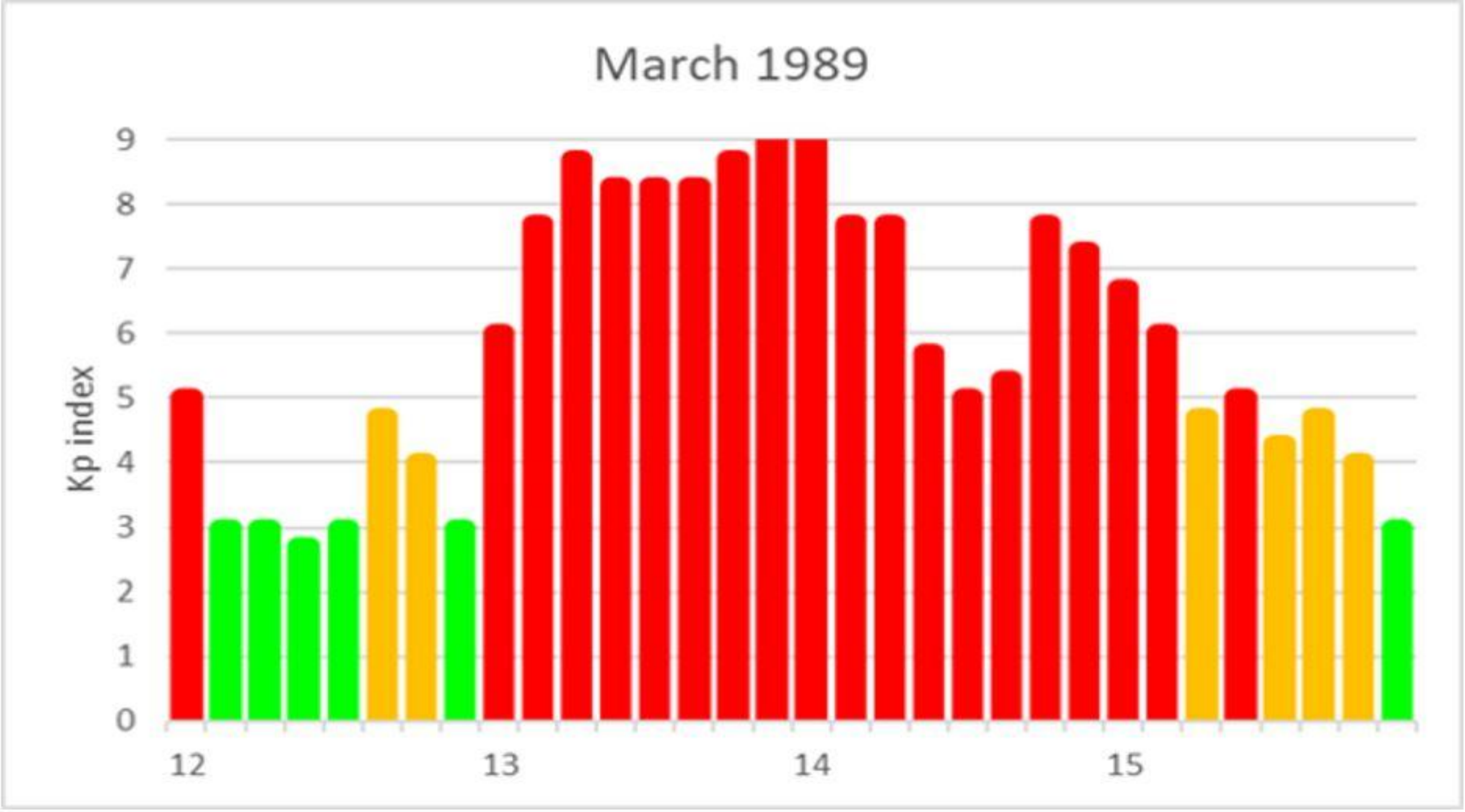


Figure 10 a.

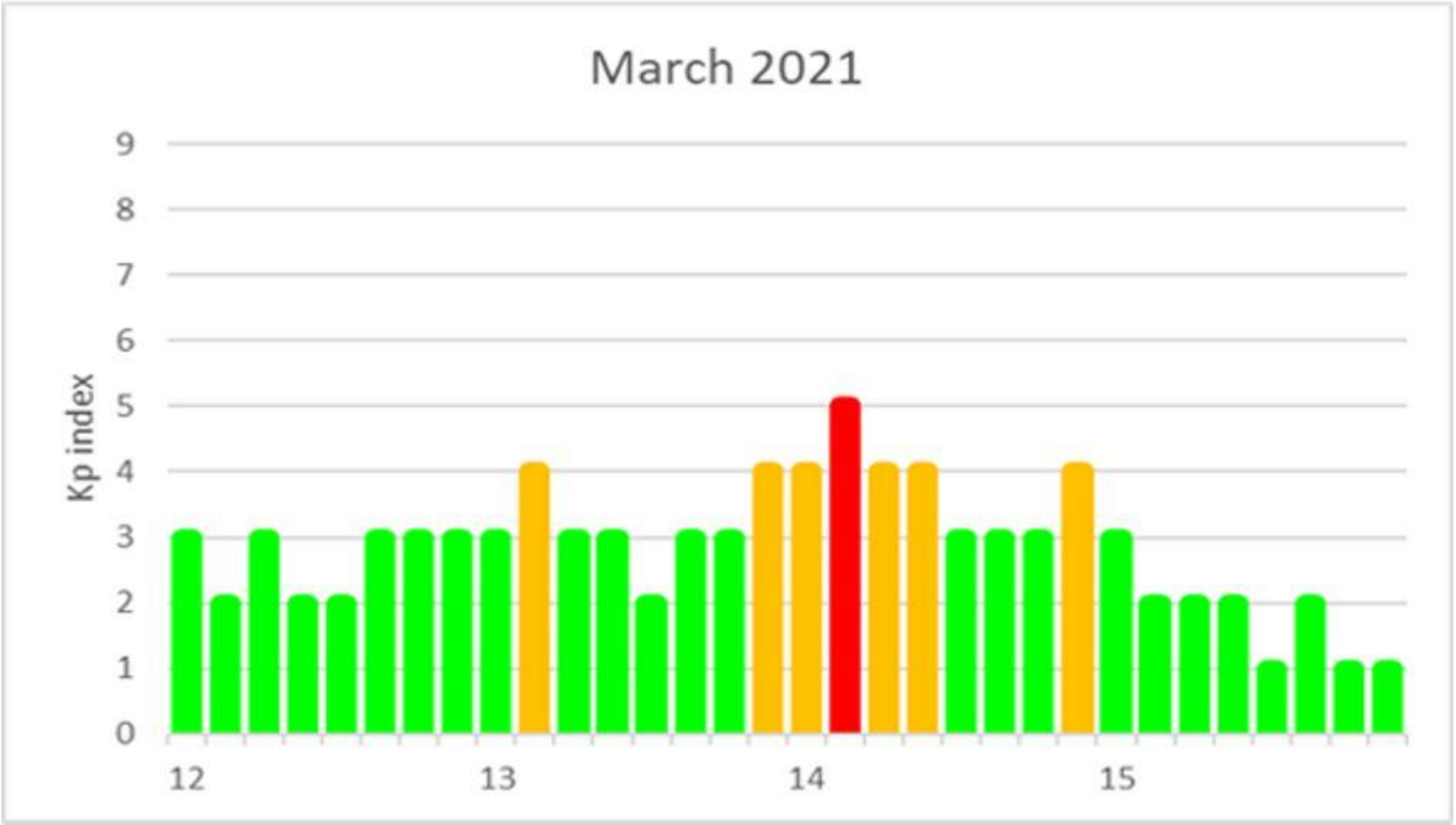


Figure 10 b.

Fig. 10 a. The geomagnetic storm of 13-14 March 1989 was the largest geomagnetic storm of the last 50 years and one of the largest of the century. We review many of the "high-latitude" observations that were made during this storm. Most of the data comes from the polar-orbiting satellites of the Defense Meteorological Satellite Program (DMSP) series. In the future we will investigate the Forbush decrease which occurred on March 13 and 14.

Fig. 10 b. The geomagnetic disturbances (with minor storm) on 13-14 March 2021 in solar minimum – just 32 years after the extreme storm on 13 – 14 March 1989 in the maximum of solar cycle 22.

CONCLUSION

In this work, using reconstructed from ground-based and space-borne instruments SEP spectra we assessed the ion production rate and the corresponding ionization effect during the second of of Halloween GLE events in October-November 2003, namely the GLE 66 on 29 October 2003. The computation was as realistic, since the dynamics of GCRs and SEPs was explicitly considered, including the giant Forbush decrease, which allowed us to make a precise assessment of the ionization effect. It was shown that the ionization effect in the polar and sub-polar region was greatly impacted by the reduced GCR flux. The computed ionization effect presented here shows compensation between SEPs and SSC and is a good basis for further studies related to the space weather.

References

1. Dorman L., P. I. Y. Velinov, A. Mishev. Global planetary ionization maps in Regener - Pfotzer cosmic ray maximum for GLE 66 during magnetic superstorm of 29–31 October 2003, Advances in Space Research (2021) (in press)

2. Velinov P. I. Y., A. Mishev (2021) Influence of Forbush effect on atmospheric ionization due to solar energtic particles. C. R. Acad. Bulg. Sci., 74 (6), 868-878.

3. Velinov P. I. Y., A. Mishev, L. Mateev (2020) Ionization effects in Regener–Pfotzer maximum due to cosmic rays during Ground Level Enhancements GLE 65, 66, 67 in October–November 2003. 16-th International Scientific Conference, 2–4 December 2020, Sofia, Proceedings SES2020 http://space.bas.bg/SES/archive/SES%202020 DOKLADI/posteri/Velinov.pdf, Session 1 - Space Physics, BAS Publishers, pp. 5-7.

Thank you for your attention!