Observations and analysis of the Ionospheric Alfven resonance mode structure in a complete 11-year solar cycle

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Accepted: 2 September 2015

Abstract The long-term data of the ionospheric Alfven resonance (IAR) observations recorded at the Ukrainian Antarctic Station “Akademik Vernadsky” from 2002 to 2013 and at Sayan Solar Observatory (Mondy, Russia) from 2010 to 2013 are analyzed. IAR fine spectral structure is studied and a previously unknown effect of splitting of the several lowest resonance modes is discovered. The diurnal and seasonal dependencies of this effect are investigated as well as the dependences of the probability of IAR and splitting detection on Solar and geomagnetic activities in the 11-year cycle. The morphological features of the splitting frequency behavior are analyzed and three main characteristic periods of the splitting are identified, namely: the development, the stationary period and the disappearing. Possible mechanisms of the splitting effect are suggested.

Key words: ionospheric Alfven resonator, splitting effect, magnetohydrodynamic waves, magnetic field

Introduction

The ionospheric Alfven resonator (IAR) is a resonance system for the shear Alfven mode of the magnetohydrodynamic (MHD) waves that is localized in the F-region of the ionosphere [Polyakov et al., 1981]. Shear Alfven waves propagate along the magnetic field line. The upper boundary of the resonance cavity is located at the heights about 1500 km where the ionospheric plasma density decreases above the F-layer maximum. At the lower boundary of the resonator (E-layer) MHD waves transform into electromagnetic ones that form spectral resonant structure (SRS) which can be detected by ground based magnetometers [Baru et al., 2012; Baru et al., 2013; Belyaev et al., 1989; Koloskov et al., 2008; Molchanov et al., 2004; Yahnin et al., 2003]. Recently, evidences of the satellite registrations of MHD waves related to IAR have appeared [Dudkin et al., 2014, Simões et al., 2012]. In general, resonances are detected within the frequency band between 0.1 and 10 Hz although in some cases the upper frequency boundary of IAR observability can reach 40 Hz [Baru et al., 2012]. Several physical mechanisms are suggested to be the origin of IAR formation [Pilipenko, 2012]. Fast feedback instability is considered to be the main mechanism of IAR excitation at high latitudes. The instability consists in the transfer of energy from plasma fluxes, that are determined by convection in the magnetosphere, into IAR frequency band [Trakhtengertz et al, 1991, Pokhotelov et al., 2001, Lysak 1991]. At the same time this mechanism cannot be proposed for middle and low latitudes because there are no convective flows at the heights lower than the plasmapause there. At these latitudes a thunderstorm activity is considered to be the main source of IAR [Surkov, Hayakawa, 2014; Surkov et al., 2005]. An alternative hypothesis is IAR excitation by ionospheric turbulence and currents produced by neutral winds in the conductive lower ionosphere. This mechanism was suggested and theoretically analyzed by [Surkov, Hayakawa, 2014; Surkov et al., 2004]. However experimental validation is necessary to confirm this assumption.

The data of IAR observations presented in literature show that the resonance parameters mostly depend on the regular characteristics of the ionosphere over the observation site [Baru et al., 2012; Baru et al., 2013; Belyaev et al., 1989; Koloskov et al., Molchanov et al., 2004; Yahnin et al., 2003]. The characteristics of SRS demonstrate fairly stable seasonal and diurnal behavior which consists in the following: 1) SRS is observed mainly in the nighttime; 2) the probability of registration reaches its maximum during the local winter and decreases significantly in the local summer; 3) SRS is detected predominantly under quiet geomagnetic conditions. Sporadic helio- and geophysical phenomena such as powerful perturbations of the magnetic field (storms and substorms), energetic particles precipitations from the radiation belts, solar flares and eclipses influence IAR behavior. Thus, IAR monitoring can be considered as an effective way of tracking space weather conditions. In 2002 the researchers of the Institute of Radio Astronomy NAS of Ukraine (IRA NASU) started IAR monitoring at the Ukrainian Antarctic Station “Akademik Vernadsky” (UAS). To the best of the authors' knowledge these records are the longest continuous data sets of IAR registration in the world. Since the resonances are a global phenomenon the simultaneous measurements at stations with big spatial separation are interesting. Therefore, IRA NASU scientists initiated IAR monitoring in the Eastern Siberia at the Sayan Solar Observatory (SSO) of the Institute of Solar-Terrestrial Physics of the Siberian branch of the Russian Academy of Sciences (ISTP SB RAS) in 2010. In

2014 a new observation site was added in the Arctic on Svalbard, Norway. The analysis of these data sets has allowed developing and validating the technique of calculation of the F_2 layer critical frequency f_0F_2 by the difference between the eigenfrequencies of IAR [Baru et al., 2013].

The large amount of experimental data obtained under different heliophysical conditions allows to investigate the fine structure of SRS and to discover a previously unknown effect of splitting of IAR lowest resonance modes [Baru et al., 2013]. In the present article the analysis of this effect is done, the primary properties of the splitting modes behavior are found and possible mechanisms of the occurrence of the effect are proposed.

The observations and data processing techniques

The main observation site is Ukrainian Antarctic Station "Akademik Vernadsky" (UAS) (65°15′ S, 64°16′ W.) where initial set of data was obtained for the period from 2002 to 2013. These experimental data were used for the investigation of the long-term dependences of the resonance characteristics on the solar activity. In addition, the SSO (51°16′ N, 100°55′ E) records from 2010 to 2013 were analyzed. It is worth to note that the geomagnetic latitudes and McIlwain L-parameter are similar (McIlwain L-parameter for UAS is 2.6, for SSO is 2.1) for both sites. IAR measurements were conducted by induction-coil magnetometers manufactured at the Lviv Center of the Institute of Space Research. The horizontal components of the geomagnetic field in the perpendicular directions along the geographical meridian (x) and parallel (y) were recorded. The magnetometers Lemi-419ANT (frequency band: 0.001÷80 Hz), and Lemi-30 (frequencies: 0.001÷40 Hz) were used at UAS and at SSO, respectively. The facts of IAR registration and splitting of the resonance modes were analyzed for every day of the year. The resonance was considered detected in the case it comprised two or more spectral maxima. After that, the probabilities of registration of these events were calculated. Then the records were processed in more details using a special software developed at IRA NASU. For every 10 minutes long interval average power $S_{xx}(f)$, $S_{yy}(f)$ and cross $S_{xy}(f)$ spectra were calculated with a frequency resolution of 0.1 Hz. These data were used for calculating the frequency dependencies of the signal's polarization parameters ($r(f)$ – ellipticity ratio, $\Psi(f)$ – position angle of the polarization ellipse, $I_p(f)$ – intensity of the polarized component, $P(f)$ – degree of polarization) using the technique described in [Koloskov et al., 2008]. Then the IAR signatures and splitting events have been identified. The values of the IAR eigenfrequencies, average frequency separations between the IAR spectral components – ΔF and the values of the splitting ΔF_{spl} were determined. The ionosondes monitored the ionospheric conditions at the observation sites. The IPS-42 ionosonde is located at UAS, and DPS-4 digisonde is situated at the distance of about two hundred kilometers from the SSO in Irkutsk. As was shown in [Baru et al., 2013], the principal ionospheric parameter for IAR is the local value f_0F_2.

The morphological features of IAR mode structure

The results of the data processing show that at both UAS and SSO sites for some records the IAR lowest resonance modes split into two satellites with the frequency separation ΔF_{spl} (Fig. 1). Typically, the splitting effect can be detected in one to twenty days per month. This number depends on the season of the year and on the phase of the 11-year solar cycle. It increases for winter and the minimum of the solar cycle and decreases for summer and the solar maximum. For some months of the summer period the splitting effect is not detected at all, however the probability of IAR registration for the summer period also decreases significantly. The splitting effect is observed in the time-frequency domain for different parameters such as signal amplitude, degree of polarization, but most clearly it is seen for the ellipticity ratio $r(f,t)$. Fig. 1 shows the diurnal dependence for $r(f,t)$ in time-frequency domain, observed at SSO on December 10, 2010. One can see that at around 12 UT (19 LT, local time) IAR peaks split into two satellites and the value of the frequency separation between them gradually increases up to the magnitude of about 0.8-1 Hz at 20 UT (3 LT). From 20 UT to 24 UT (7 LT) the ΔF_{spl} value is decreasing. The effect is evident for the first three IAR modes. With the increase of the number of the IAR resonance mode, the start time of the splitting insignificantly shifts to the nighttime. It is worth to note that both split and unsplit parts of IAR lines have almost circular counterclockwise polarization (the ellipticity ratio is about -1). The calculation showed that other polarization parameters of the IAR have the same values at unsplit and split sections for both satellites. Therefore, the polarization analysis cannot be used to select the satellites.

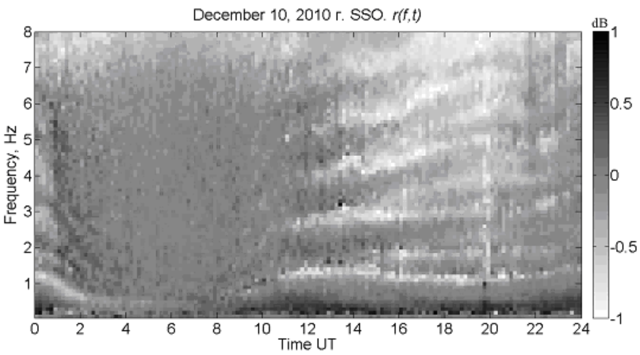
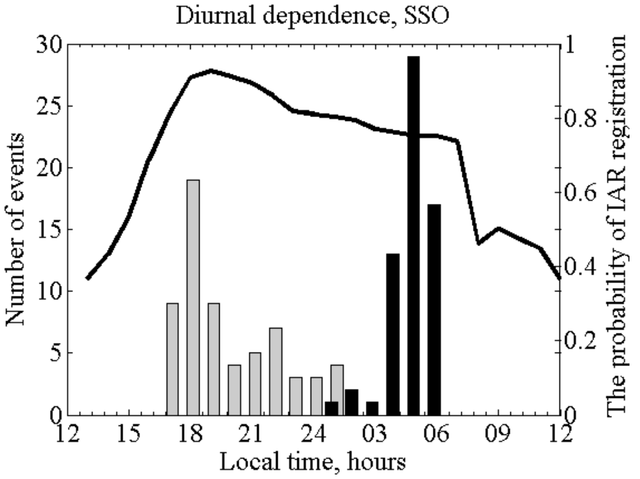
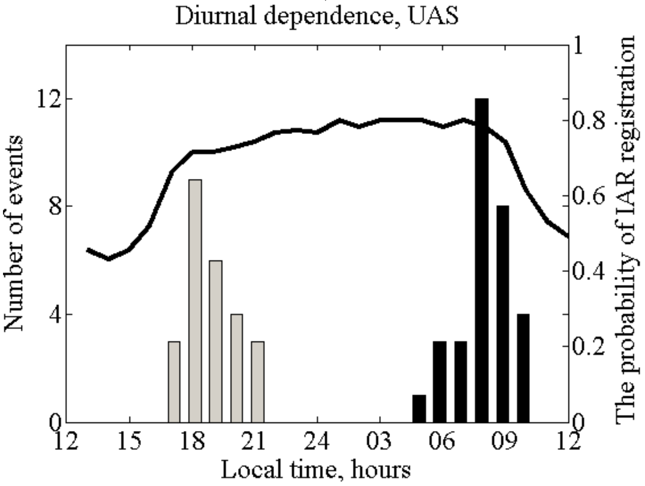


Fig. 1. Daily spectrogram of the ellipticity ratio observed at SSO on December 10, 2010.

Figures 2.a and 2.b show the diurnal dependences in the splitting at SSO and UAS, respectively. Fig. 2 demonstrates that the splitting at both sites is only observed during the local night. The observation time for most of the events corresponds to the interval of the maximum probability of IAR registration that is from 6 PM to 6 AM at SSO and from 6 PM to 9 AM at UAS.



a)



b)

Fig. 2. Diurnal dependences of the splitting beginning (grey columns) and disappearance (black columns) at SSO (a) and UAS (b). The probability of IAR registration at every station is marked with the line (vertical axis at the right).

The different duration of the observation periods is associated with longer duration of the night at UAS.

Fig. 3.a demonstrates that the splitting is observed at both sites during the local winter only and is absent for other seasons. The analysis shows that diurnal and seasonal dependences for the number of splitting events correspond to the similar behavior of the probability of IAR observation, but it is expressed more clearly for the splitting. It should be noted, that it cannot be determined unambiguously that the splitting is absent during the daytime, because of the complexity of the effect observations. ΔF is becoming too small and IAR modes are almost merged at daytime. At the same time it is evident from the observations that the splitting is absent in spring, summer and autumn at both sites and this fact should be taken into account for further physical modelling and analysis.

Fig. 3.b illustrates the IAR behavior during the 11-year solar cycle. Blue bars show the probability of IAR registration; green bars correspond to the probability of splitting registration calculated for every year from 2002 to 2013 at UAS. White and black bars demonstrate the corresponding parameters for SSO in 2010-2013. The vertical axis at the left side of the plot presents the values of the probabilities. As one can see for UAS both probabilities behave in a similar way and reaches its maximum that corresponds to the solar minimum in 2009.

Let's consider the asymmetry of the interannual variations of the probabilities. For the previous solar maximum of 2002-2003 the splitting effect at UAS was not registered at all; the probability of IAR registration was significantly lower in comparison with the last solar maximum of 2012-2013.

The data for SSO are available for the last 4 years only. It is worth noting that the probabilities of IAR registration and splitting registration demonstrate similar behavior for both stations within this period. The probability of IAR registration at SSO is higher than at UAS and it does not change significantly from year to year for both stations. The probability of splitting registration decreases from 2010 to 2013 stronger at UAS than at SSO.

The solar and local geomagnetic activities are shown at Fig. 3.b in inverted format (right axis). The value of the average annual Wolf numbers is marked by dash line. The Wolf numbers are presented according to the web link http://www.sidc.be/silso/datafiles of the World Data Center of Royal Observatory of Belgium. Geomagnetic activity is characterized by average annual local K-indices calculated at the magnetic observatory of UAS – AIA. As seen from Fig. 3.b, the long-term variations of both IAR and splitting probabilities are anticorrelated with solar and local geomagnetic activities.

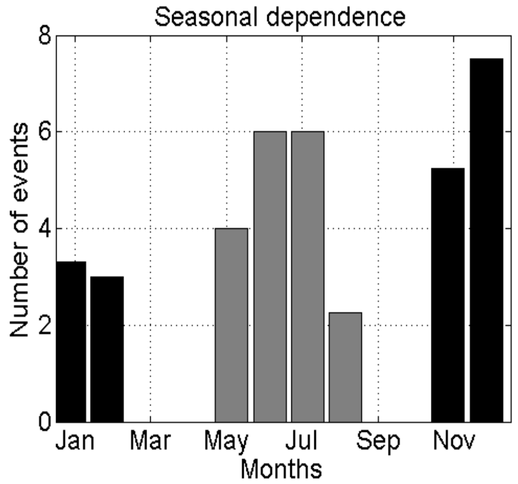
Discussion and conclusions

Information about inverse dependence of the probability of IAR registration on geomagnetic and solar activities is presented in literature [Hayakawa et al., 2004; Molchanov et al., 2004; Yahnin et al., 2003; Belyaev et al., 2000], but those results were obtained from fragmented records and do not characterize IAR behavior during the solar cycle. In the present paper, the long-term continuous data series are detailed analyzed.

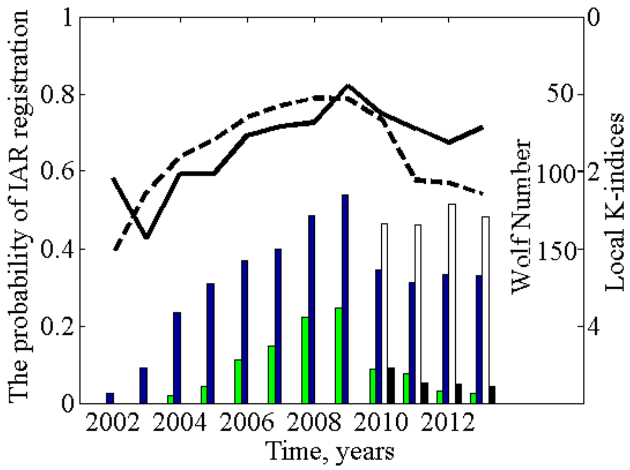
First of all the large absolute value of the correlation coefficient between average annual probability of IAR registration and the Wolf numbers (-0.89) has been found. Thus inter-annual changes of the solar activity can be considered as the main factor that determines the long-term variations of IAR parameters. But the relationship between solar activity and IAR is not linear. Biggest differences are at the high level of the solar activity. As can be seen from Fig. 3.b, from 2002 to 2006 the probability of IAR registration grows faster than the Wolf number decreases. During the minimum and the rising phase of the solar cycle the relationship is close to linear.

Our earlier study performed for the period of the solar minimum showed a weak inverse dependence of IAR observability on the value of the local K-indices at

UAS [Baru et al., 2013]. The current study carried out for the period of a complete solar cycle shows a clear inverse dependence of IAR observability on the average annual value of K-indices at UAS (Fig 3.b) with correlation coefficient -0.76. Differences in the curves behavior are observed only in 2002 when the averaged K-indices decreased despite the maximum of the solar spots. Obviously, the solar activity is the major factor which determines IAR observability at this time.



a)



b)

Fig. 3. a) Average annual number of splitting events at UAS (grey columns) and at SSO (black columns); b) Average annual probability of IAR registration at UAS (blue columns) and at SSO (white columns) and probability of splitting registration at UAS (green columns) and at SSO (black columns). Average annual values Wolf numbers (dashed line) and local K-indices for UAS (full line).

It should be noted, that the correlation coefficient between the variation of the probability of splitting registration and of the probability of IAR registration is 0.82 for the 12 years of observations. The high level of the statistical relationship between both processes shows that the number of occurrence of the splitting grows in the period of the solar minimum most likely because of the increase of the overall IAR observability rather than due to the dependence on the solar cycle.

Let us consider the splitting value dependence on the critical frequency of F_2 layer. It is evident from the literature that the frequency spacing between neighboring resonance modes of IAR – ΔF is in inverse dependency to the critical frequency of F_2 layer - f_0F_2 [Baru et al., 2013; Belyaev, et al., 1989; Belyaev, et al., 1999]. The authors of the paper [Baru et al., 2014] proposed a technique for estimating the critical frequency of F_2 layer above the observation point via ΔF value measured for IAR observations. In the present study we have analyzed whether this relationship is maintained itself for the value of splitting ΔF_{spl} and what the behavior of the ratio - $\Delta F_{spl}/\Delta F$ is. The averaged dependences $\Delta F(t)$ (black solid curve), $\Delta F_{spl}(t)$ (dashed curve), $f_0F_2(t)$ (gray curve) (Fig. 4.a) and $\Delta F_{spl}(t)/\Delta F(t)$ ratio (Fig 4.b) are shown for all the cases when the splitting was observed for 10 hours or more at both UAS and SSO sites from 2010 to 2013.

Figure 4.a shows that the shape of curves for the averaged frequency spacing $\Delta F(t)$ and for the splitting value $\Delta F_{spl}(t)$ is different. $\Delta F_{spl}(t)$ is characterized by less evening growth, existence of an almost stationary region and a sharp morning decrease. Fig. 4.b demonstrates the splitting value $\Delta F_{spl}(t)$ normalized by the frequency spacing $\Delta F(t)$. The curve consists of three characteristic intervals which can be well approximated by linear functions. They are as follows: the time interval of the rise of the splitting - 1 (~16-20 LT, when the normalized splitting value increases linearly), the stationary interval - 2 (~20-02 LT, when the normalized splitting value doesn't change) and the relaxation interval - 3 (~02-05 LT, when the normalized splitting value decreases linearly). Note that the confidential intervals do not exceeded 0.5 (do not reach the half of the intermode frequency difference) for the stationary region of $\Delta F_{spl}(t)/\Delta F(t)$.

Several hypotheses can be proposed to explain the mechanism of the discovered splitting effect. The first of them is the assumption that the split satellites correspond to different branches of the normal modes of IAR, namely: shear Alfven and fast magnetosonic (FMS) waves. Originally, IAR was associated with shear Alfven waves [Polyakov et al., 1981; Belyaev et al., 1989]. But the analysis of the plasma wave propagation showed that FMS mode can also be trapped in the same cavity. FMS waves can form SRS similar to shear Alfven waves. The theoretical analysis performed by [Surkov et al., 2004; Surkov, Hayakawa, 2014] has shown that IAR spectra contain peaks both due to both the shear Afven and FMS modes. Their calculations showed that attenuation of the shear mode is greater than that of the fast mode and hence FMS waves can play an important role in the formation of the IAR spectra especially for nighttime conditions. It should also be noted that the behavior of the FMS mode is differed from that of the shear Alfven mode. This difference depends on the ionospheric conductivities, as well as daily variations of their dispersion properties [Surkov et al., 2004; Surkov, Hayakawa, 2014]. Therefore, it is possible to suggest that additional peaks in split IAR spectra are explained

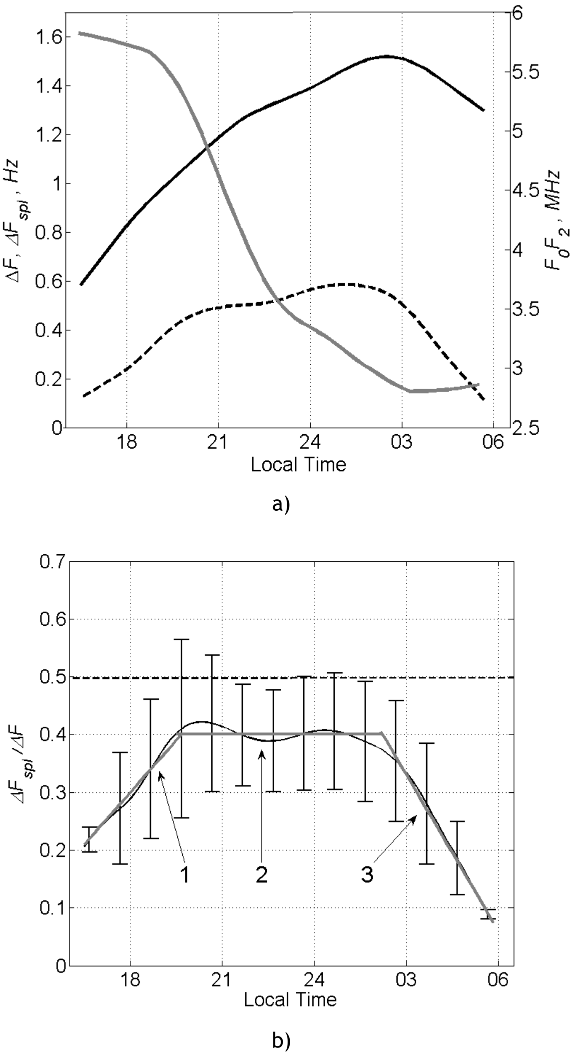


Fig. 4. a) Diurnal dependences for *ΔF(t)* (black solid curve), *$\Delta F_{spl}(t)$* (dashed curve), *$f_0F_2(t)$* (gray curve) smoothed within 3-hour window and averaged throw the all analyzed splitting events; b) *$\Delta F_{spl}(t)/\Delta F(t)$* smoothed within 3-hour window (black curve). The approximations of the splitting relative value for the time interval of the rise of the splitting - 1, the stationary interval - 2 and the relaxation interval – 3 are marked with grey segments.

by the appearance of FMS modes during nighttime conditions along with shear Alfven modes. The verification of this suggestion requires additional modeling and computations, which are beyond the scope of the article. Another possibility is the assumption that the splitting phenomenon is related to the appearance of two effective reflective borders at the bottom ionospheric or top plasmospheric parts of the resonator. Another hypothesis to be considered is the possibility of a leakage of the resonance oscillations from the magnetic conjugate point that has different illuminating conditions, another value of the critical frequency and consequently other resonance frequencies.

Summarizing, we note that:

1) The features of the IAR signal behavior in complete solar cycle were analyzed. The significant inverse correlation of the probability of the ionospheric Alfven resonance registration at high latitude site located in Southern hemisphere (Ukrainian Antarctic Station) with geomagnetic and solar activities has been confirmed as a result of processing of long-term continuous data set.
2) Fine spectral structure of the ionospheric Alfven resonance was studied. Previously unknown effect of splitting of several lowest resonance modes has been discovered. The probability of the splitting appearance has been studied on diurnal, seasonal and 11-year time scales.
3) The morphological features of the splitting effect were analyzed. Three main characteristic periods of the splitting have been identified, namely: the development, the stationary period and the disappearing.
4) The splitting phenomena could be associated with the appearance of fast magnetosonic mode in addition to the sheared Alfven modes. Two alternative hypothetic mechanisms of splitting were proposed also.

Acknowledgements

The authors are thankful to the National Antarctic Scientific Center of Ukraine, Ministry of Education and Science of Ukraine for supporting the long-term monitoring of IAR at UAS "Akademik Vernadsky". This research was partially supported by the National Academy of Sciences of Ukraine projects "Yatagan-2" (N 0111U000063) and «Spitsbergen-2015» (N 0115U004079).

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