Journal of Atmospheric and Solar-Terrestrial Physics 122 (2015) 119–128

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Incoherent scatter ion line enhancements and auroral arc-induced Kelvin–Helmholtz turbulence

J. Ekeberg [a,b,*], K. Stasiewicz [c,d], G. Wannberg [a], T. Sergienko [a], L. Eliasson [a]

[a] Swedish Institute of Space Physics, P.O. Box 812, SE-981 28 Kiruna, Sweden
[b] ABB Schweiz AG, Corporate Research, CH-5405 Baden-Dättwil, Switzerland
[c] Swedish Institute of Space Physics, P.O. Box 537, SE-751 21 Uppsala, Sweden
[d] Space Research Centre, Polish Academy of Sciences, Warsaw, Poland

ARTICLE INFO

Article history:
Received 18 April 2011
Received in revised form
15 October 2014
Accepted 30 October 2014
Available online 7 November 2014

Keywords:
Auroral ionosphere
Radar observations
Plasma waves and instabilities

ABSTRACT

We present two cases of incoherent-scatter ion line enhancements in conjunction with auroral arcs drifting through the radar beam. The up- and downshifted ion line shoulders as well as the spectral region between them are enhanced equally and simultaneously. The power enhancements are one order of magnitude above the thermal level and are concentrated in less than 15 km wide altitude ranges at the ionospheric *F* region peak. The auroral arc passages are preceded by significantly enhanced ion temperatures in the *E* region, assumed to be caused by transient electric fields associated with velocity shears. We use a Hall MHD model of velocity shears perpendicular to the geomagnetic field and show that a Kelvin–Helmholtz instability will grow for the two presented cases.

1. Introduction

The ion lines of incoherent-scatter spectra are formed predominantly by scattering of radio waves off ion-acoustic waves. Due to Landau damping, the two spectral lines are broadened and merge into a "double-humped" line with a downshifted and an upshifted shoulder, corresponding to scattering off ion-acoustic waves propagating respectively away from and towards the radar. Occasionally, when the ion-acoustic waves are destabilised (e.g. [Rosenbluth and Rostoker, 1962]) and the radar beam is nearly parallel to the geomagnetic field, one or both of the ion line shoulders are enhanced up to 4–5 orders of magnitude above the thermal level ([Grydeland et al., 2004]). This is referred to as *naturally enhanced ion-acoustic lines* (NEIAL).

NEIAL have been seen in spectra from the Millstone Hill incoherent scatter radar ([Foster et al., 1988]), the European Incoherent Scatter (EISCAT) UHF ([Rietveld et al., 1991]), the EISCAT VHF ([Collis et al., 1991]) and the EISCAT Svalbard Radar ([Sedgemore-Schulthess et al., 1999; Buchert et al., 1999]). For further details on NEIAL observations and suggested generation mechanisms, refer to the review by Sedgemore-Schulthess (2001) and references therein.

Michell et al. (2008) reported Poker Flat Incoherent Scatter Radar (PFISR) observations of enhanced ion lines at low altitudes (250–350 km) with power enhancements of 3–5 times the thermal level and substantial power enhancement also between the ion line shoulders. Similar observations were done by Michell and Samara (2010) who related the ion line enhancements to nightside dynamic thin auroral arc structures. One of the cases was consistent with Michell et al. (2009), where the enhanced ion lines were seen on the boundary of thin auroral arcs.

These observations cannot be easily explained in terms of current NEIAL models. Michell et al. (2008) suggested a possible connection between their enhancement events and broad-band extremely low-frequency (BBELF) wave activity, based on the auroral morphology accompanying their observations. Another mechanism was suggested by Ekeberg et al. (2010) who showed that compressive solitary waves could generate the observed spectral enhancement. Recently Ekeberg et al. (2012) showed that these so-called *spectrally uniform ion line power enhancements* (SUIPE) occur at or close to the ionospheric *F* region density peak (at altitudes between 210 km and 280 km) and often are localised to an altitude range of less than 20 km. This is in strong contrast to observations of classical NEIAL, which are typically observed ([Rietveld et al., 1996]) around 500 km altitude. No cases, where both ion-acoustic shoulders are enhanced simultaneously, were seen below 300 km altitude. Also, NEIAL are often seen simultaneously over a height range of several hundred kilometres (e.g., [Rietveld et al., 1991]).

We present two cases of similar ion line enhancements as those studied by Michell et al. (2008, 2009); Michell and Samara (2010); Ekeberg et al. (2010); Ekeberg et al. (2012) in conjunction with

* Corresponding author.
E-mail address: jonas.ekeberg@ch.abb.com (J. Ekeberg).

http://dx.doi.org/10.1016/j.jastp.2014.10.018
1364-6826/

auroral arcs drifting through the radar beam. Both auroral arc passages were preceded by enhanced ion temperatures, which is a signature of large perpendicular electric fields. We use these *E* region ion temperatures to calculate the associated electric fields, based on the assumption of dominating ionospheric Joule heating. This is done on the leading and lagging side of the respective arcs in the direction of propagation. The transient changes of the electric field are associated with large velocity shears, which are used as the starting point for studying the onset of a Hall MHD (Magnetohydrodynamic) Kelvin–Helmholtz (K–H) instability close to the *F* region peak. The instability growth rate is calculated for both cases and we propose that the associated wave turbulence can explain the spectrally uniform ion line power enhancements.

The K–H instability (e.g., [Chandrasekhar, 1961]) grows when layers of plasma or fluid have a relative tangential velocity, causing an exchange of momentum between the two layers. The K–H instability occurs in neutral fluids and plasmas in the laboratory as well as in astrophysical and space plasmas (see e.g. [Miura, 1997, and references therein]). In space plasmas, the K–H instability has been extensively studied at the Earth's magnetopause, but also at the unmagnetised planets Venus and Mars (e.g. Amerstorfer et al., 2010, and references therein).

The spatial scales of the K–H instability are comparable to the bulk scales of the plasma, thus it is well described by fluid plasma theory. Linear theories for the K–H instability based on MHD have been developed (e.g., [Miura and Pritchett, 1982]) but these models do not cover all spatial scales where K–H instabilities may occur ([Miura, 1987]). In order to extend the validity of the one-fluid description, K–H instability models based on Hall MHD were developed (e.g., [Fujimoto and Terasawa, 1991; Opp and Hassam, 1991]). The K–H instability model utilised in this study is based on such a description.

The following section describes the experimental setup and provides an observational context for the K–H model equations, which are introduced in Section 3. Section 3 furthermore describes the analysis of the observational data. In the subsequent sections, the results are presented and discussed before the paper ends with some concluding remarks.

2. Observational method

The measurements presented here are based on observations by the EISCAT Svalbard Radar (ESR) and the Finnish Meteorological Institute (FMI) all-sky camera on Spitsbergen.

The ESR ([Wannberg et al., 1997]) is a 500 MHz incoherent scatter radar located on Spitsbergen at 78° 09′11″N, 16° 01′44″E. The system comprises two parabolic dish antennae of 32 m and 42 m in diameter. The 32-m dish is fully steerable in azimuth and elevation, whereas the 42-m dish is fixed along the local direction of the geomagnetic field with an azimuth of 181° and an elevation of 81.6°.

Beginning in March 2007, the International Polar Year experiment was carried out using both dishes of the ESR. The experiment used a $32 \times 30\,\mu$s alternating code ([Lehtinen and Häggström, 1987]) with maximum range and time resolutions of 4.5 km and 6 s, respectively. It was run until the end of February 2008 and focused on lower heights (<500 km).

The FMI all-sky camera on Spitsbergen is part of the MIRACLE (Magnetometers Ionospheric Radars All-sky Cameras Large Experiment) network and is located at 78° 08′52.8″N, 16° 02′34.8″E, less than 2 km from the ESR. The CCD has a spatial resolution of 512×512 pixels and there are interference filters for the wavelengths 427.8 nm (blue), 557.7 nm (green) and 630.0 nm (red). The time resolution for the green filter is 20 s and for the other two 60 s. In the present study, data from the green filter, which has a 1 s exposure time, have been utilised.

3. Analytical method

3.1. Model equations

The conventional set of MHD equations is adequate for describing plasma phenomena on spatial scales L larger than both the electron and ion Larmor radii ($\rho_{e,i}$) and temporal frequencies ω slower than both the electron and ion cyclotron frequencies ($\omega_{ce,ci}$). By including the *Hall term* (e.g., [Krall and Trivelpiece, 1973]), this validity can be extended to the spatial scales $\rho_e, \rho_i \ll L$ and $\rho_e \ll L \ll \rho_i$ and temporal frequencies $\omega_{ci}, \omega_{ce} \ll \omega$ and $\omega_{ci} \ll \omega \ll \omega_{ce}$. In the limit of $L \sim \rho_i$, the anisotropic ion stress tensor should be retained in order to account for Finite ion Larmor Radius (FLR) effects ([Roberts and Taylor, 1962]). FLR effects also become important in high-β plasmas, $\beta_i = \rho_i^2/\lambda_i^2$, where the ion inertial length $\lambda_i = V_A/\omega_{ci} \lesssim \rho_i$. In an ionospheric *F* region plasma, $\rho_i \lesssim 10$ m and $\beta_i \sim 10^{-5}$. Thus, FLR effects can be neglected.

The equations of Hall MHD for a plasma with singly charged positive ions and electrons are given by (e.g., [Krall and Trivelpiece, 1973])

$$\frac{\partial N}{\partial t} + \nabla\cdot(N\mathbf{V}) = 0 \tag{1}$$

$$Nm_i\frac{\mathrm{d}\mathbf{V}}{\mathrm{d}t} = \mathbf{J} \times \mathbf{B} - \nabla\cdot\mathrm{P} \tag{2}$$

$$\frac{1}{Ne}\mathbf{J} \times \mathbf{B} = \mathbf{E} + \mathbf{V} \times \mathbf{B}, \tag{3}$$

where $\mathbf{V}$, $\mathbf{J}$, P are the centre of mass velocity, current density and total pressure tensor, respectively. The left hand side of the generalised Ohm's law, (3) is the Hall term. In deriving (2) and (3), collisions, electron pressure gradients and terms related to electron inertia were neglected and $N_e \approx N_i \approx N$ was assumed, thus neglecting charge separation effects. The neglection of electron pressure gradients in the generalised Ohm's law rests on the assumption ([Krall and Trivelpiece, 1973]) that the typical spatial scales $\tilde{L}$ and speeds $\tilde{V}$ fulfil

$$\frac{\tilde{L}\tilde{V}\omega_{ce}m_e}{k_B T_e} \gg 1, \tag{4}$$

which will be verified *a posteriori*. The system is closed by the Maxwell's equations,

$$\nabla \times \mathbf{B} = \mu_0\mathbf{J}, \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}, \tag{5}$$

neglecting the displacement current, and an isotropic ($\nabla\cdot\mathrm{P} \rightarrow \nabla p$) equation of state,

$$p = p_0 n^\gamma \tag{6}$$

where γ is the polytropic pressure exponent for the total pressure and n is the density normalised to the background. The isotropic and polytropic pressure relations are applicable for plasmas with $\beta = 2\mu_0 p_0/B_0^2 < 1$, hence for simplicity they are chosen instead of the more general polybaric pressure model ([Stasiewicz, 2005]). As pointed out by Hassam and Huba (1988) and also implemented by Opp and Hassam (1991), the pressure tensor terms in (2) can be neglected in the case of supersonic flow speeds (i.e. $V \gg c_s$). This is, however, in general not the case for the ionospheric *F* region.