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Advances in Space Research xxx (2017) xxx–xxx

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ADVANCES IN SPACE RESEARCH (a COSPAR publication)

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Kelvin–Helmholtz instability in a twisting solar polar coronal hole jet observed by *SDO*/AIA

I. Zhelyazkov [a,*], T.V. Zaqarashvili [b,c,d], L. Ofman [e,f,g], R. Chandra [h]

[a] *Faculty of Physics, Sofia University, 1164 Sofia, Bulgaria*
[b] *IGAM, Institute of Physics, University of Graz, 8010 Graz, Austria*
[c] *Abastumani Astrophysical Observatory at Ilia State University, 0162 Tbilisi, Georgia*
[d] *Space Research Institute, Austrian Academy of Sciences, 8042 Graz, Austria*
[e] *Catholic University of America, Washington, DC 20064, USA*
[f] *NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA*
[g] *Visiting, Department of Geosciences, Tel Aviv University, Ramat-Aviv, Tel Aviv 69978, Israel*
[h] *Department of Physics, DSB Campus, Kumaun University, Nainital 263 001, India*

Received 21 April 2017; received in revised form 1 June 2017; accepted 2 June 2017

Abstract

We investigate the conditions under which the fluting ($m = 2$), $m = 3$, and $m = 12$ magnetohydrodynamic (MHD) modes in a uniformly twisted flux tube moving along its axis become unstable in order to model the Kelvin–Helmholtz (KH) instability in a twisting solar coronal hole jet near the northern pole of the Sun. We employed the dispersion relations of MHD modes derived from the linearized MHD equations. We assumed real wavenumbers and complex angular wave frequencies, namely complex wave phse velocities. The dispersion relations were solved numerically at fixed input parameters (taken from observational data) and varying degrees of torsion of the internal magnetic field. It is shown that the stability of the modes depends upon five parameters: the density contrast between the flux tube and its environment, the ratio of the external and internal axial magnetic fields, the twist of the magnetic field lines inside the tube, the ratio of transverse and axial jet's velocities, and the value of the Alfvén Mach number (the ratio of the tube axial velocity to Alfvén speed inside the flux tube). Using a twisting jet of 2010 August 21 by *SDO*/AIA and other observations of coronal jets we set the parameters of our theoretical model and have obtained that in a twisted magnetic flux tube of radius of 9.8 Mm, at a density contrast of 0.474 and fixed Alfvén Mach number of $\cong 0.76$, for the three MHD modes there exist instability windows whose width crucially depends upon the internal magnetic field twist. It is found that for the considered modes an azimuthal magnetic field of 1.3–1.4 G (computed at the tube boundary) makes the width of the instability windows equal to zero, that is, it suppress the KH instability onset. On the other hand, the times for developing KH instability of the $m = 12$ MHD mode at instability wavelengths between 15 and 12 Mm turn out to be in the range of 1.9–4.7 min that is in agreement with the growth rates estimated from the temporal evolution of the observed unstable jet's blobs in their initial stage.

Keywords: Magnetohydrodynamics; Waves; Instabilities; Twisting coronal hole jets; Numerical methods

1. Introduction

Rotational motion seems to be a common property of various kinds of jets and prominences in the solar atmosphere detected from multi-wavelength observations with high spatial resolution and high cadence using

* Corresponding author.
E-mail address: izh@phys.uni-sofia.bg (I. Zhelyazkov).

http://dx.doi.org/10.1016/j.asr.2017.06.003
0273-1177/

Please cite this article in press as: Zhelyazkov, I., et al. Kelvin–Helmholtz instability in a twisting solar polar coronal hole jet observed by *SDO*/AIA. Adv. Space Res. (2017), http://dx.doi.org/10.1016/j.asr.2017.06.003

Atmospheric Imaging Assembly (AIA) (Lemen et al., 2012), on board the *Solar Dynamics Observatory* (*SDO*) (Dean Pesnell et al., 2012), the *Interface Region Imaging Spectrograph* (*IRIS*) (De Pontieu et al., 2014), and the *Hinode* (Kosugi et al., 2007) Extreme-ultraviolet Imaging Spectrometer (EIS) (Culhane et al., 2007) alongside the earth-basing THEMIS and the Swedish 1-meter solar telescopes. Solar rotating and helical structures are termed as solar tornadoes. In fact the word 'tornado' was initially associated with solar prominences (see, e.g., Pettit (1932) and Schmieder et al. (2017) and references therein), but Pike and Mason (1998) used the same term to describe transition region macrospicules seen by the *Solar and Heliospheric Observatory* (*SOHO*) (Domingo et al., 1995) which (the spicules) have no relation with prominences. Kamio et al. (2010) on using *Hinode*/EIS and the Solar Ultraviolet Measurements of Emitted Radiation instrument (SUMER) (Wilhelm et al., 1995) on the *SOHO* were able to measure the line of sight (LOS) motions of both macrospicule and coronal jets. At the same time, with the help of the X-ray Telescope (XRT) (Golub et al., 2007) on *Hinode* and Sun–Earth Connection Coronal and Heliospheric Investigation (SECCHI) instrument suite (Howard et al., 2008) on the *Solar TErrestrial RElations Observatory* (*STEREO*) (Kaiser et al., 2008) the authors traced the evolution of the coronal jet and the macrospicule. Wedemeyer-Böhm et al. (2012) performing observations with AIA on board *SDO* and the Crisp Imaging Spectropolarimeter (CRISP) (Scharmer et al., 2003) at the Swedish 1-m Solar Telescope discovered a swirling motion at different heights in the solar atmosphere. These swirls, also dubbed 'magnetic tornadoes' (Wedemeyer et al., 2013), the authors found to originate in the chromosphere, but do not appear to be related to any filamentary structure. These structures can play an important role for channeling energy from the chromosphere into the corona.

In addition to macrospicules, rotational motions have been observed in the so cold Type II spicules (De Pontieu et al., 2012). Soft X-ray jets can also exhibit rotational motions. Moore et al. (2013) exploring 54 polar X-ray jets from movies taken by the X-ray Telescope on *Hinode* and in the He II 304 Åband of the *SDO*/AIA have obtained rotational speeds of the order of $60\,\mathrm{km\,s^{-1}}$. Recently Moore et al. (2015) studied 14 large solar jets that erupted in polar coronal holes and were observed in the outer corona beyond $2.2 R_\odot$ in images from the *SOHO*/Large Angle Spectroscopic Coronagraph (LASCO) (Brueckner et al., 1995). There is no surprise that rotational motions were detected in EUV solar jets, too. Shen et al. (2011) have presented an observational study of the kinematics and fine structure of an unwinding polar jet, with high temporal and spatial observations taken by the *SDO*/AIA and the Solar Magnetic Activity Research Telescope. In a similar way, Chen et al. (2012) using the multi-wavelength data from the *SDO*/AIA, studied a jet occurring in a coronal hole near the northern pole of the Sun and have obtained jet's parameters of the same orders as those in Shen et al. (2011) study. Zhang and Ji (2014) using the multi-wavelength observations in the EUV passbands from the *SDO*/AIA have detected the onset of jet eruption coinciding with the start time of a C1.6 solar flare. A rotating coronal hole jet observed with *Hinode* and the *SDO*/AIA on 2011 February 8 at around 21:00 UT was reported by Young and Muglach (2014). Recently, Filippov et al. (2015) analyzed multi-wavelength and multi-viewpoint observations with *STEREO*/SECCHI/EUVI and *SDO*/AIA of a helically twisted plasma jet formed during a confined filament eruption on 2013 April 10–11.

It is well established that in magnetically structured solar atmosphere various jets with axial mass flow like spicules, surges, EUV and X-ray jets can become unstable against the so called Kelvin–Helmholtz instability (KHI)—for reviews see, e.g., Zhelyazkov (2015), Nakariakov et al. (2016), Zhelyazkov et al. (2017) and the references therein. Recall that the instability exhibits itself as a vortex sheet evolving near jet's boundary which (the vortex sheet) can become unstable to the spiral-like perturbations at small spatial scales provided that jet's axial velocity exceeds some critical/threshold value (Ryu et al., 2000).

Previous studies devoted to the KHI modeling in rotating cylindrical jets were carried out by Bodo et al. (1989, 1996). These authors studied the stability of a rotating, magnetized cylindrical axial flow of radius a through an ambient unmagnetized medium by considering that all perturbations of the velocity $\boldsymbol{v}$, magnetic field $\boldsymbol{B}$, and pressure p obey the basic equations of ideal magnetohydrodynamics for a polytropic fluid and are in the form $f(r)\exp[\mathrm{i}(-\omega t + kz + m\theta)]$. Having derived a Bessel equation for the pressure perturbation p_1 and appropriate expression for the radial $\boldsymbol{v}_1$-component the authors merge the solutions in both media via the boundary conditions for continuity of the total (thermal + magnetic) pressure and the Lagrangian displacement (the ratio of radial velocity perturbation component and the angular frequency in the corresponding medium) at the interface $r = a$ and obtain the dispersion relation of the normal MHD modes propagating along the jet. In their two papers, Bodo et al. (1989, 1996) have studied analytically and numerically the stability conditions of both axisymmetric, $m = 0$ (Bodo et al., 1989), and non-axisymmetric, $|m| \geqslant 1$ (Bodo et al., 1996), modes. A step forward was the study of Zaqarashvili et al. (2015), who examining the stability/instability status or rotating jets, modeling them as moving untwisted/twisted magnetized flux tubes embedded in a homogeneous background magnetic field, have considered the case when the flow velocity is also twisted, thus generalizing in incompressible plasma approximation the wave dispersion equation derived by Bodo et al. (1989). To finish our survey on the KH modeling in rotating solar jets we should mention the articles of Terradas et al. (2008) and Soler et al. (2010) who explored the nonlinear instability