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Alfvén ionization in the atmospheres of brown dwarfs

C. R. Stark[1], Ch. Helling[1], D. A. Diver[2], and P. B. Rimmer[1]

[1] School of Physics and Astronomy, University of St Andrews, St Andrews, KY16 9SS, UK, e-mail: `craig.stark@st-andrews.ac.uk`
[2] School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, UK

Abstract. Ionization processes and the generation of plasmas are critical elements in a holistic understanding of substellar atmospheres. We propose Alfvén ionization as a mechanism for producing localized pockets of ionized gas in the atmosphere, having sufficient degrees of ionization ($\geq 10^{-7}$) that they constitute plasmas. This paper outlines the criteria required for Alfvén ionization to occur and demonstrate its applicability in Brown Dwarf atmospheres. Our results show that degrees of ionization ranging from $10^{-6} - 1$ can be obtained. Furthermore, Alfvén ionization alters the atmospheric chemistry via the creation of new ionic species not normally available in contemporary, thermally-driven atmospheric models. Observable consequences include continuum Bremsstrahlung emission superimposed with spectral lines from the plasma ion species. The presence of an atmospheric plasma opens the door to a multitude of plasma and chemical processes not yet considered in current atmospheric models.

Key words. Stars: atmospheres

1. Introduction

Brown Dwarfs are observed to be strong sources of coherent radio emission (e.g. see Route & Wolszczan 2012; Hallinan et al. 2007, 2008; Berger 2002; Berger et al. 2010), inferring the presence of a plasma population in their surrounding atmospheric envelopes. Ionization processes occur in the atmospheres of Brown Dwarfs that create volumes of ionised gas, with sufficient degrees of ionization that they become plasmas. For a plasma, the degree of ionization must be $\gtrsim 10^{-7}$. A plasma is a quasineutral gas of charged and neutral particles where the dynamics of the charged particles is dominated by their collective, long-range electromagnetic influence as opposed to short-range, binary interactions. For an ionised gas to exhibit collective plasma behaviour the entirety of the gas does not need to be ionized, a partially or weakly ionised plasma is sufficient. For Brown Dwarfs, the degree of thermal ionization is insufficient to qualify the atmospheric ionized gas as a plasma.

Helling and co-workers have made progress in investigating ionization processes in substellar atmospheres (Helling et al. 2011a,b, 2013). Helling et al. (2011b) used Drift-Phoenix model atmospheres to investigate the effect of dust-induced collisional ionization. They found that ionization by turbulence-induced dust-dust collisions was

Send offprint requests to: C. R. Stark the most efficient of the ionization processes considered but the electron density produced was insufficient to significantly improve the degree of ionization. However, the resulting charged dust grains that compose the atmospheric clouds, are susceptible to inter-grain electrical discharge events (Helling et al. 2011a) that can enhance the free electron population.

We propose Alfvén ionization as an effective and efficient mechanism for producing volumes of plasma in Brown Dwarf atmospheres.

2. Alfvén Ionization

Consider a constant stream of neutral gas with a flow speed v_0 impinging on a low-density stationary, magnetized, seed plasma. The inflowing neutrals elastically scatter the plasma ions, producing a significant charge imbalance which cannot be rectified immediately due the restricted motion of the magnetized electrons (see Fig. 1). The resulting self-electrostatic field of the exposed electrons continues to grow until the potential difference inhibits further ionic displacement, meaning the electrostatic potential energy is now equal to the maximum kinetic energy $\frac{1}{2}m_{\rm gas}v_0^2$ (where $m_{\rm gas}$ is the mass of a neutral atom) of an ion as a result of a collision (Alfvén 1960). The persistent self-repulsion of the electrons accelerates the local electrons to an equivalent energy, ionizing the incoming neutral atoms that have an electron-impact ionization threshold, $e\phi_I$, that is less than $\frac{1}{2}m_{\rm gas}v_0^2$ (MacLachlan et al. 2009, 2013).

Alfvén ionization requires that: (i) the seed plasma is strongly magnetized; and (ii) the neutral gas flow reaches a critical speed, $v_{\rm c} = (2e\phi_I/m_{\rm gas})^{1/2}$. Potassium has one of the smallest critical speeds ($v_c = 4.63\,{\rm km\,s^{-1}}$) whereas Hydrogen (Helium) have the largest speeds $v_c = 51.02\,{\rm km\,s^{-1}}$ ($34.43\,{\rm km\,s^{-1}}$).

2.1. The magnetized seed plasma

Alfvén ionization requires an initial low-density, magnetized seed plasma in the atmosphere. In substellar atmospheres the required seed plasma can be easily generated from local discharge events (lightning) in mineral clouds (Chang et al. 2010) where, in analogy with terrestrial lightning strikes, can attain $n_{\rm e} \approx$

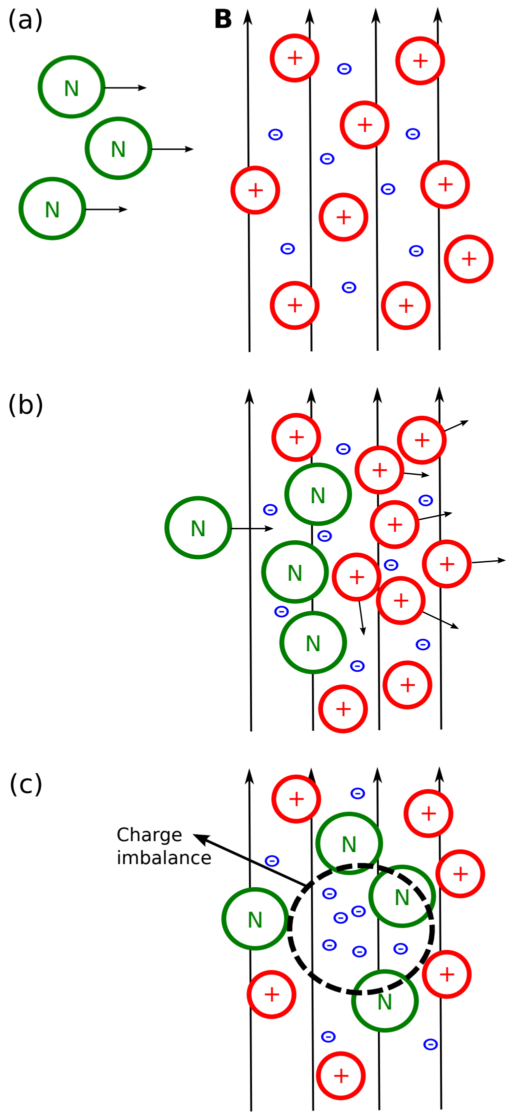

Fig. 1. The Alfvén ionization process: (a) A constant stream of neutral gas impinges on a low-density localized, magnetized plasma; (b) The inflowing neutral atoms collide with and displace the plasma ions; (c) the displaced ions leave behind a significant charge imbalance that accelerates electrons to energies sufficient to ionize the local gas via electron-neutral impact ionization.

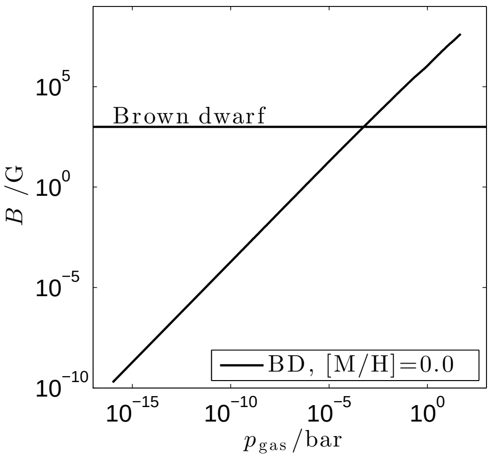

Fig. 2. The required minimum magnetic flux density B for the plasma to qualify as magnetized (Eqn. 3) in a BD atmosphere. The horizontal black lines show the typical average, global (large-scale) magnetic flux densities for BDs ($B \approx 1$ kG).

10^{17} cm^{-3}. Cosmic ray bombardment can also boost the electron density by $n_e \approx 10^4$ cm^{-3} (Rimmer & Helling 2013).

To satisfy condition (i) the background seed plasma must be magnetized. The criterion for magnetized electrons is $\omega_{ce} \gg \nu_{coll}$, where $\omega_{ce} = eB/m_e$ is the electron cyclotron frequency; m_e is the mass of an electron; and ν_{coll} is the electron-neutral collision frequency. The criterion for magnetised electrons can be rewritten as

$$\frac{eB}{m_e} \gg n_{gas}\langle\sigma v\rangle, \tag{1}$$

$$B \gg \frac{m_e n_{gas}\langle\sigma v\rangle}{e}, \tag{2}$$

$$\approx \frac{m_e n_{gas}\pi r_0^2}{e}\left(\frac{k_B T_e}{m_e}\right)^{1/2}, \tag{3}$$

where the approximations $\langle\sigma v\rangle \approx \pi r_0^2\langle v\rangle$ and $\langle v\rangle = (k_B T_e/m_e)^{1/2}$ have been made; and r_0 is the atomic radius. Drift-Phoenix model atmosphere simulations (Witte et al. 2009, 2011) provide the atmospheric pressure and temperature structure (p_{gas}, T_{gas}) for BD atmospheres. Fig. 2 shows the criteria for a magnetized plasma (Eq. 3) in the atmospheres of BDs characterized by $\log g = 5.0$, $T_{eff} = 1500$ K, for solar metallicity ([M/H] = 0.0). In these calculations $r_0 \approx 10^{-8}$ cm and $T_e \approx T_{gas}$. Typical average, global (large-scale) magnetic flux densities for BDs are estimated to be of the order of ≈ 1 kG (Donati & Landstreet 2009; Reiners 2012). For $p_{gas} \approx 10^{-10}$ bar, $n_{gas} \approx 10^8$ cm^{-3} and $T_e \approx 700$ K then the magnetic flux density required for the plasma to be considered magnetized is $B \gtrsim 10^{-4}$ G. As the gas density increases, the plasma electrons are more likely to collide with the neutrals inhibiting their gyration and so disrupt the influence of the ambient magnetic field on their motion. Over a large atmosphere pressure range ($10^{-15} \lesssim p_{gas} \lesssim 10^{-2}$ bar) the magnetized plasma criterion is easily achievable and the minimum local magnetic flux density required is $\lesssim 10^4$ G.

2.2. Atmospheric flows: the critical speed v_c

In general, for the species expected to populate substellar atmospheres the critical speed, v_c, required is of the order of 1-10 km s^{-1}. Meteorological studies of substellar atmospheric flows and circulation have shown that flow speeds $v \approx 1 - 10$ km s^{-1} can be obtained (e.g. see Rauscher & Menou 2010). It is worth noting that these flow speeds are bulk fluid commodities, averaged over an underlying particle energy distribution; there will always be a high energy tail of the distribution function that will allow access to larger critical speeds.

3. Degree of Alfvén Ionization in Brown Dwarf atmospheres

We are interested in Alfvén ionization in the atmospheres of BDs. We consider an example atmosphere using the Drift-Phoenix code which describes non-equilibrium cloud formation in substellar envelopes (Woitke & Helling 2003; Helling et al. 2008a,b) characterized by $\log g = 5.0$, $T_{eff} = 1500$ K, for solar metallicity. There is a broad range of observed $\log g$ and T_{eff} for Brown Dwarfs e.g. for WISE 1828+2650, $T_{eff} \approx 300$ K (Beichman et al. 2013); and Cha Hα 8, $T_{eff} \approx 3000$ K (Luhman 2007). Our value of T_{eff} lies approximately in the middle of this range and is consistent with a number of

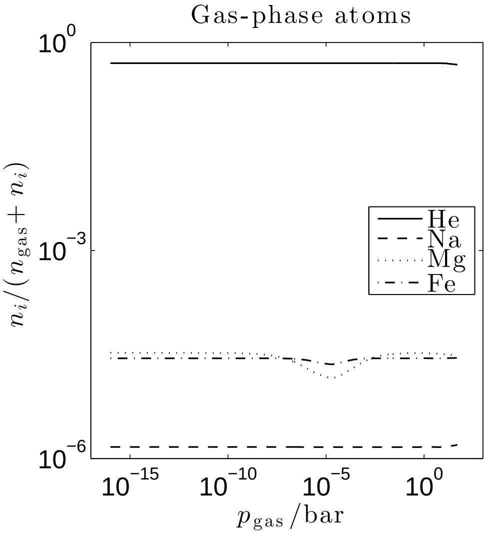

Fig. 3. The degree of Alfvén ionization for a BD atmosphere for specific gas-phase atoms. For these species the degree of ionization is $\geq 10^{-7}$ and therefore constitutes a plasma.

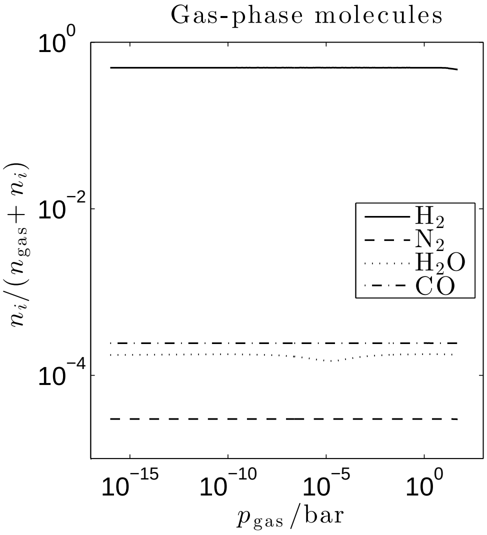

Fig. 4. The degree of Alfvén ionization for a BD atmosphere for specific gas-phase molecules. For these species the degree of ionization is $\geq 10^{-7}$ and therefore constitutes a plasma.

Brown Dwarfs e.g. 2MASS J0850+1057 AA (Burgasser et al. 2010). In general, $\log g$ is not well constrained and so we follow contemporary modelling and use $\log g = 5$ which is consistent with current observed Brown Dwarfs (e.g. GD165B; Kirkpatrick et al. 1999).

Assuming the required conditions can be met, Alfvén ionization can ionize the entirety of the gas in a localized volume, leaving a plasma with an electron number density equal to the gas component number density (assuming 100% ionization) plus the initial seed magnetized plasma number density. Figs. 3 and 4 show the resulting degree of ionization from Alfvén ionization, if specific individual species constituting the atmospheric gas are entirely ionized (on their own) in a localized atmospheric pocket. In general, if in a localized atmospheric pocket a particular species can be 100% ionized, then the species with the greatest number density will yield the highest degree of ionization. For the atmosphere of interest, Figs. 3 and 4 show the species that yield the highest degree of ionization. To summarise: if entirely ionized on their own He, Fe, Mg, Na, K, H_2, CO, H_2O, N_2, SiO and AlOH all consistently increase the degree of ionization beyond 10^{-7} throughout the model atmosphere considered here. Note the species in the preceding list are ordered in terms of their resulting degree of ionization, going from highest to lowest for atoms and molecules respectively. Therefore, these species if ionised via Alfvén ionization will create volumes of atmospheric plasma.

4. Impact on atmosphere and observables

The injection of a significant amount of electrons, positive ions and radicals, as a result of Alfvén ionization, has important consequences for the subsequent atmospheric chemistry. The amplified ionized species allow more complex chemistry to occur than if there were only thermal processes. Furthermore, the amplified free electron population increases the likelihood that these electrons attach themselves to the ambient neutral atoms, molecules or dust particles enhancing the consequent chemistry.

Charged particle surfaces grow via the accumulation of neutral atoms and an electrostatically attracted ion flux and so will grow faster than the uncharged case when there is only a neutral flux. The electric field of the charged grains accelerate the plasma ions towards the grain and they react on the surface. Upon reaching the surface the ions are electrostatically energized helping catalyse chemical reactions that are otherwise energetically unfavourable at low-temperatures.

If the atmospheres of Brown Dwarfs are populated by magnetized plasmas then it could be observable as Bremsstrahlung emission with a characteristic spectrum depending on the nature of the source. Bremsstrahlung radiation is produced by the motion and mutual interaction of the plasma particles. The power radiated per unit volume per unit solid angle per unit angular frequency interval (the Bremsstrahlung emission coefficient, ϵ_ω) for a thermal plasma is given by

$$\epsilon_\omega(T_\mathrm{e}) = \frac{8}{3\sqrt{3}} \frac{Z^2 n_\mathrm{e} n_i}{m_\mathrm{e}^2 c^3} \left(\frac{e^2}{4\pi\epsilon}\right)^3 \left(\frac{m_\mathrm{e}}{2\pi k_B T_\mathrm{e}}\right)^{1/2} \times \bar{g}(\omega, T_\mathrm{e}) \exp\left(-\frac{\hbar\omega}{k_B T_\mathrm{e}}\right), \qquad (4)$$

where $\bar{g}$ is the Gaunt factor; Z_i is the ion charge number; ω is the photon angular frequency; n_e and n_i is the electron and ion number density of the plasma respectively (Boyd & Sanderson 2003). In the regime $\hbar\omega \geq k_\mathrm{B} T_\mathrm{e}$, the slope of a log-linear plot of ϵ_ω gives a measure of the plasma electron temperature T_e. If the electron temperature can be obtained independently, the plasma density could be determined using the Bremsstrahlung emission coefficient (Boyd & Sanderson 2003). Superimposed on the continuum plasma emission would be spectral lines from the plasma ion species (e.g. He, Mg, Fe, Na or H_2, CO, H_2O, N_2) constituting the atmospheric plasma. The identification of these lines would allow the characterization of the plasma species.

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