Alfvén Ionization in the atmospheres of Brown Dwarfs

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Observations of radio and X-ray emission from Brown Dwarfs (low-mass, ultra-cool substellar objects) suggest that such objects harbour atmospheric magnetized plasmas. However, the degree of thermal ionization is insufficient to qualify the ionized component as a plasma. We propose Alfvén ionization as a mechanism for producing localized pockets of ionized gas in the atmosphere, having a sufficient degree of ionization ($\geq 10^{-7}$) that they constitute plasmas. We outline the criteria for Alfvén ionization and demonstrate its applicability to Brown Dwarfs.

Alfvén Ionization

Brown Dwarfs (BDs) are objects whose mass is sufficiently low that Hydrogen fusion cannot be sustained. As a result, such low-mass objects are very cool allowing the formation of mineral clouds in their atmospheres. The formation of the clouds depletes the ambient atmospheric gas and alters the objects electromagnetic spectrum. Furthermore, charged cloud particles can participate in electrical discharge events [1] that may produce an observable diagnostic. BDs can be strong sources of coherent radio emission [2, 3], inferring the presence of a plasma population in their surrounding envelopes. Observations of the M9 dwarf TVLM 513-46546 characterize the radio emission as variable with a periodicity consistent with the estimated period of rotation and with additional periodic bursts [3]. We propose Alfvén ionization as a mechanism to produce the required plasma that that could be the source of the radiation.

Consider a constant stream of neutral gas with a flow speed v_0 impinging on a low-density stationary, magnetized, seed plasma. It is assumed that this seed plasma is localized by the ambient magnetic field and is of a similar chemical composition as the neutral gas. 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. 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 [4]. 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 $\frac{1}{2}m_{\rm gas}v_0^2$ [5].

For Alfvén ionization we require that: (i) the seed plasma is strongly magnetized; and (ii) the neutral gas flow reaches a critical speed, $v_c = (2e\phi_I/m_{\text{gas}})^{1/2}$. Atoms such as Potassium have the smallest critical speeds ($v_c = 4.63$ kms^{-1}) whereas Hydrogen (Helium) have the largest speeds $v_c = 51.02$ kms^{-1} (34.43 kms^{-1}). In general, for the species expected to populate substellar atmospheres the critical speed required is $v_c \approx O(1-10$ km s$^{-1})$. Meteorological studies of substellar atmospheric flows and circulation have shown that flow speeds $v \approx 1-10$ kms^{-1} can be obtained (e.g. see [6]). 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.

The magnetized seed plasma

To initiate Alfvén ionization we require an initial low-density, magnetized seed plasma in the atmosphere. Due to elastic collisions with the neutrals the ions are sent off to participate in a Larmor orbit, exposing a pocket of unbalanced electrons with a length scale equal to the ion Larmor radius R_{Li}. To allow a localized pocket of electrons (a charge imbalance) of length scale R_{Li} to be created it is required that the Debye length must be much smaller than the ion Larmor radius: $\lambda_D \ll R_{Li}$. This criterion can be recast in terms of the ambient electron number density n_e, of the seed plasma required to initiate Alfvén ionization,

$$n_e^{\text{seed}} \gg \frac{\varepsilon_0 k_B T_e B^2}{m_i^2 v_{\perp i}^2}. \tag{1}$$

To calculate what threshold electron number density n_e^{seed} is required we shall set $v_{\perp i} = v_0 \approx$ 1 kms^{-1} and approximate $m_i \approx 10^{-27}$ kg. Although some of the neutral species have a critical speed $O(10$ kms$^{-1})$, setting $v_{\perp i} = 1$ kms^{-1} gives an upper limit to n_e^{seed}. Therefore, the number density of the magnetized seed plasma must satisfy,

$$n_e^{\text{seed}} \gtrsim 10^2 T_e B^2 \ \ [\text{cm}^{-3}]. \tag{2}$$

In substellar atmospheres thermal ionization produces an electron population with $T_e \approx 10^2 - 10^3$ K. In general, plasma electron temperatures can be $T_e \approx 10^2 - 10^6$ K, where terrestrial lightning yields $T_e \approx 10^4$ K.Typical average, global (large-scale) magnetic flux densities for BDs are estimated to be of the order of ≈ 1 kG [7]. For $B \approx 10^3$ G and $T_e \approx 10^2 - 10^6$ K, the resulting range in the seed electron number density is $n_e^{\text{seed}} \gtrsim 10^6 - 10^{16}$ cm^{-3}. In substellar atmospheres the required seed plasma can be easily generated from local discharge events (lightning) in mineral clouds where in analogy with terrestrial lightning strikes can attain $n_e \approx 10^{17}$ cm^{-3} [8] . Cosmic ray bombardment can also boost the ambient electron density by $n_e \approx 10^4$ cm^{-3} [9].

Furthermore, To satisfy condition (i) for Alfvén ionization the background seed plasma must be magnetized (i.e. the electrons are localised by the magnetic field). 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

$$B \gg \frac{m_e n_{\mathrm{gas}} \langle \sigma v \rangle}{e}, \tag{3}$$

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 [10, 11] provide the atmospheric pressure and temperature structure (p_{gas}, T_{gas}) for BD atmospheres. Fig. 1 shows the criteria for a magnetized plasma (Eq. 3) in the atmospheres of BDs characterized by $\log g = 5.0$, $T_{\mathrm{eff}} = 1500$ K, for solar metallicity ([M/H] = 0.0). In these calculations $r_0 \approx 10^{-8}$ cm and $T_e \approx T_{\mathrm{gas}}$. For $p_{\mathrm{gas}} \approx 10^{-10}$ bar, $n_{\mathrm{gas}} \approx 10^8$ 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 ($10^{-15} \lesssim p_{\mathrm{gas}} \lesssim 10^{-2}$ bar) the magnetized plasma criterion is easily achievable and the minimum local magnetic flux density required is $\lesssim 10^4$ G.

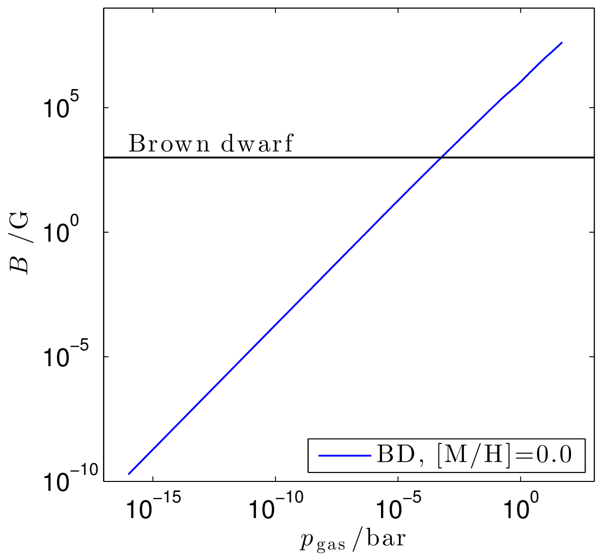

Figure 1: The required minimum B for a magnetized plasma (Eq. 3) in a BD atmosphere. The black line show the typical average, large-scale magnetic flux density for a BD.

Degree of Alfvén Ionization in Brown Dwarf atmospheres

We are interested in Alfvén ionization in the atmospheres of BDs; we utilise the results Drift-Phoenix [10, 11] and consider an example model atmosphere. These model atmospheres are determined by three fundamental parameters: $\log g = 5.0$, $T_{\mathrm{eff}} = 1500$ K, for solar metallicity. 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. 2(a) and 2(b) show the resulting degree of ionization from Alfvén ionization, if specific individual species constituting the atmospheric gas are entirely ionized (on

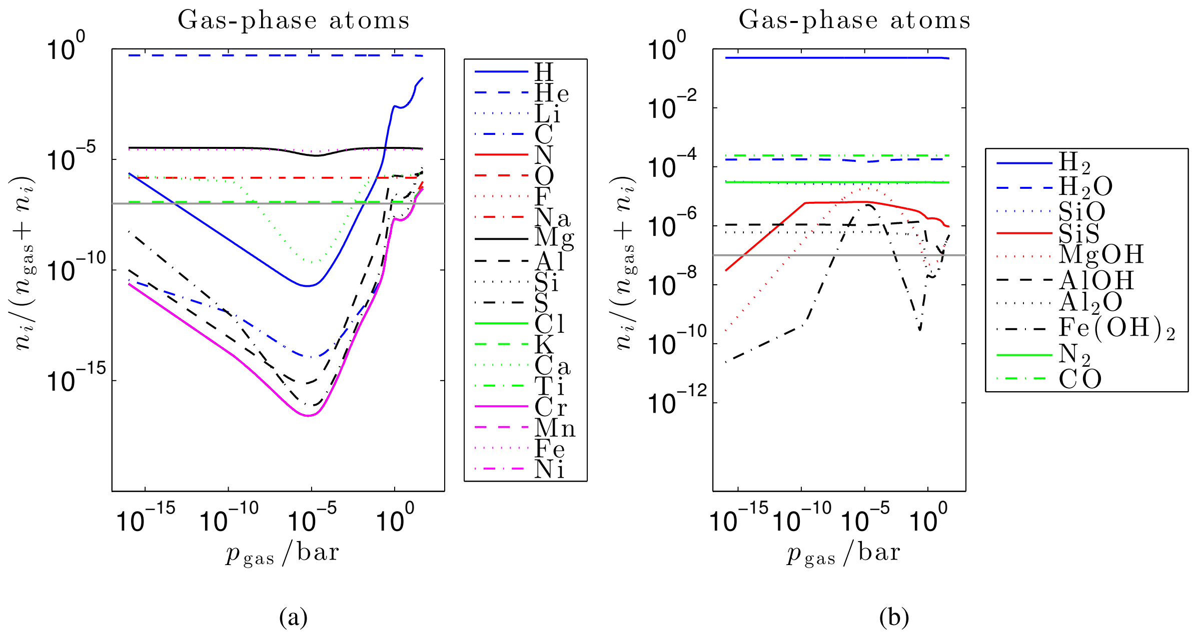

Figure 2: Degree of Alfvén ionization for a BD atmosphere. The grey horizontal line signifies 10^{-7}, the threshold required for a plasma. The dependence with p_{gas} is due to the underlying species number density which is affected by element depletion as a result of cloud formation.

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. To summarise: if entirely ionized on their own He, Fe, Mg, Na, H_2, CO, H_2O, N_2 and SiO all consistently increase the degree of ionization beyond 10^{-7} throughout the model atmosphere considered here.

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