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Alfvén ionization in exoplanetary atmospheres

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Abstract

Observations of continuous radio and sporadic X-ray emission from low-mass objects suggest such objects harbour an atmospheric, localized plasma. For low-mass objects, the degree of thermal ionization is insufficient to qualify the ionized gas as a plasma, posing the question: what ionization processes can efficiently produce the required plasma? We propose Alfvén ionization as a simple mechanism for producing localized pockets of ionized gas in the atmosphere, having sufficiently large degrees of ionization ($\geq 10^{-7}$) that they constitute plasmas. We outline the criteria required for Alfvén ionization to occur and justify it's applicability in the atmospheres of low-mass objects such as giant gas planets, brown dwarfs and M-dwarfs for both solar and sub-solar metallicities. We find that Alfvén ionization is most efficient at mid to low atmospheric pressures where a seed plasma is easier to magnetize and the pressure gradients needed to drive the required neutral flows are the smallest. For the model atmospheres considered, our results show that degrees of ionization ranging from $10^{-6} - 1$ can be obtained. Observable consequences include continuum Bremsstrahlung emission, superimposed with spectral lines from the plasma ion species (e.g. He, Mg, H_2 or CO lines). Forbidden lines are also expected from the metastable population as a consequence of the Penning Effect. The presence of an atmospheric plasma opens the door to a multitude of plasma and chemical processes not yet considered in current atmospheric models.

1. Scientific context

Ultracool dwarfs (low-mass objects with spectral type later than M7) can be strong sources of radio emission which infers the presence of atmospheric plasmas. Observations of the M9 dwarf TVLM 513-46546 at 4.88 and 8.44 GHz characterize the radio emission as variable with a periodicity consistent with the estimated period of rotation $\approx$ 2 hrs [2] and additional periodic (1.96 hrs) bursts with 100% circularly polarized [1]. Similar radio emission signatures have been detected from other ultracool dwarfs such as T6.5 dwarf 2MASS J1047+21 [3], the M8.5 dwarf LSR J1835+3259 and the L3.5 dwarf 2MASS J00361617+1821104, with brightness temperatures indicating the emission comes from a coherent source, most likely an electron cyclotron maser instability [4].

Helling and co-workers have considered the effects of plasma phenomena in substellar atmospheres [5, 6, 7]. They used DRIFT-PHOENIX model atmospheres [6] to investigate the effect of dust-induced collisional ionization. They found that ionization by turbulence-induced dust-dust collisions was 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 [5].

2. Alfvén ionization

In Alfvén ionization a constant stream of neutral gas impinges on a low-density magnetized plasma. The inflowing neutral atoms collide with and displace the plasma ions, leaving behind a significant charge imbalance that accelerates electrons to energies sufficient to ionize the local gas via electron-neutral impact ionization. Alfvén ionization requires an initial, low-density magnetized seed plasma and a neutral gas flow that reaches a critical threshold speed [8].

3. Resulting degree of ionization in exoplanetary atmospheres

We are interested in Alfvén ionization in the atmospheres of gas giant planets, brown dwarfs and M-dwarfs. We consider an example atmosphere using

DRIFT-PHOENIX (giant gas planets, GP) characterized by $\log g = 3.0$, $T_{\rm eff} = 1500$ 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. Fig. 1 shows 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. 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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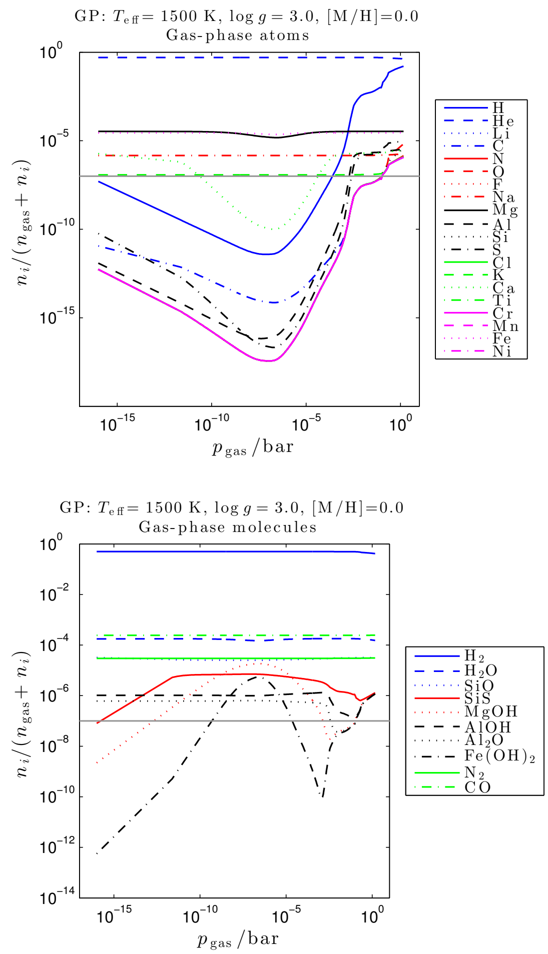

Figure 1: The degree of ionization $f_e = n_i/(n_{\rm gas}+n_i)$ resulting from Alfvén ionization for a gas giant planet (GP: $T_{\rm eff} = 1500$ K, $\log g = 3.0$), assuming initially solar elemental abundances ([M/H] $= 0.0$). The top plot shows f_e for atoms; and the bottom plot shows f_e for selected molecules. The grey horizontal line signifies $f_e = 10^{-7}$, the degree of ionization required to constitute a plasma.