EPJ Web of Conferences **46**, 04005 (2013)
DOI: 10.1051/epjconf/20134604005

The Short Circuit Instability in Protoplanetary Disks:

Processing high temperature minerals

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Abstract. We introduce a magneto-hydrodynamic instability which occurs, among other locations, in the inner, hot regions of protoplanetary disks, and which alters the way in which resistive dissipation of magnetic energy into heat proceeds. This instability can be likened to both an electrical short circuit and lightning, as it concentrates the dissipation of magnetic energy by means of the enhanced release of free electrons. This instability can generate very high temperatures, making it an excellent candidate for thermally processing protoplanetary disk solids, from annealing silicates to melting chondrules or even CAIs.

1 Introduction

Protoplanetary accretion disks have a large reservoir of energy tied up in the gravitational potential energy of the disk. While this energy is more than adequate to explain observations such as the melting of solids which is witnessed by chondrules in chondritic meteorites, tapping the energy is difficult. The energy is released as a result of the accretion flow, which is generally thought to be mediated by the magneto-rotational instability (or MRI, [1]). In this picture, the accretion motion converts the gravitational energy into shearing orbital motion. Through the MRI, the orbital shear amplifies the magnetic field, which in turn dissipates either by driving hydrodynamical motions (which dissipate viscously) or, more likely, through resistive dissipation of the currents which create the magnetic fields. The extraction of the energy drives further accretion, and the cycle continues. However, both theory and numerical simulation find that the MRI cannot generate magnetic fields whose energy density is much greater than the thermal energy density of the gas. Dissipation of the magnetic fields will then be unlikely to raise the temperature by more than a factor of two, and even that is barely plausible given that such heating would drive an outflow which cools through adiabatic expansion.

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2 Chondrules

Chondrules are small grains which make up a large mass fraction of chondritic meteorites. They show evidence of having been rapidly heated to temperates of 1800 K before cooling at rates which are both slower than free radiation to a cold background, and far faster than disk dynamical time scales [2, 3]. In a phenomenon known as complementarity, chondrules, and the matrix grains which make up the remainder of chondrites, are correlated together in that their total elemental make up is Solar, even when the individual make up of chondrules and matrix grains varies substantially [4, 5]. This requires the matrix grains and chondrules that make up a single chondritic meteorite to come from the same portion of the proto-solar nebula. Further, the matrix grains cannot have been heated significantly [6–8]. This requires a spatially intermittent heating mechanism. In a further complication, many chondrules show evidence of multiple heating events [9, 10], so the heating mechanism must be ubiquitous, but not too ubiquitous.

3 Short Circuits

The MRI is thought to be active everywhere in a protoplanetary disks where the ionization fraction is adequate that the resistivity not quench the instability. As the resistivity in such disks is far greater than the viscosity, the bulk of the energy in the magnetic fields is expected to be dissipated into heat in the current sheets which are a general feature of MHD turbulence [11]. If the temperature of the disk is of the order of 1000 K or warmer, this has interesting consequences [12, 13]. In those circumstances, thermal ionization of alkali metals (particularly potassium) dominates the ionization fraction and is the chief source of free electrons. However, this temperature is far below the energy associated with ionizing potassium, so the ionization fraction of the potassium is low, and extremely temperature dependent (varying by a factor of two over a range of 30 K). This implies that as the center of a current sheet heats through normal Ohmic resistivity, more electrons are released, locally increasing the conductivity, and further that the conductivity increase with temperature is strong. The system then evolves to channel more of the current through the hot, high conductivity region as shown in figure 1. This can result in an increased local heating rate in a phenomenon akin to an electrical short, leading to high current density, high temperature current sheets far narrower than one started with. Such a geometry is well suited for both chondrule formation (those solids which do pass through a narrowed current sheet) and matrix preservation (the nearby solids that don't pass through a current sheet).

Under idealized circumstances, in the absence of cooling, this instability always triggers when the conductivity increases with temperature [12], although the growth rate of the instability may be too slow for even approximate idealization if the initial current sheet is too broad or the magnetic field is too weak. However, strong magnetic fields (plasma $\beta \sim 1.5$) will trigger the instability for initial current sheet widths appropriate to a protosolar nebula [13].

The introduction of cooling through radiative transfer can quench the instability [13]. If it does so, it will tend to do so at two temperatures: at temperatures of $\sim$ 1200 K, radiative cooling becomes dramatically more efficient as organics are destroyed and the gas opacity drops extremely steeply over a small temperature range. This can occur when the instability is relatively weak (lower magnetic field strength or wider initial current sheet) and the scenario is appropriate for rapid annealing of amorphous silicates into crystalline silicates [14], as those temperatures are inadequate to melt the silicates.

A second large drop in the gas opacity occurs at 1600 K, where silicates melt (and chondrules form), and is reached for stronger instabilities. Even stronger instabilities, with initial parameters still reasonable for the proto-solar nebula, do not halt at either of those opacity drops, and instead saturate

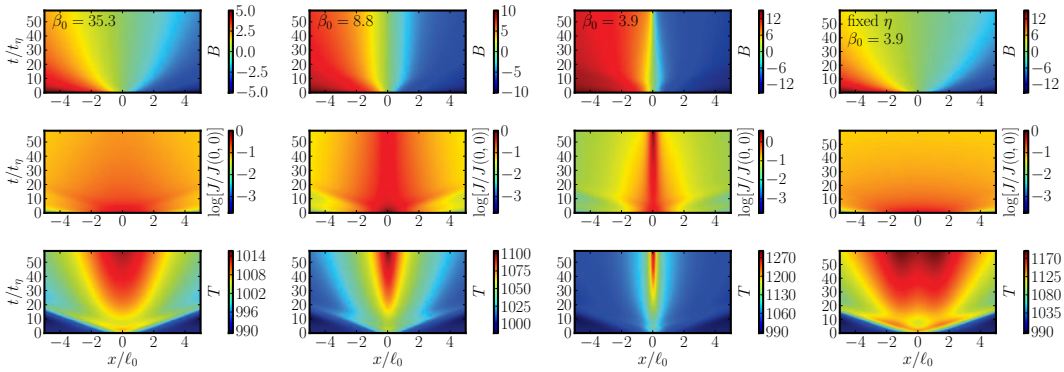

Figure 1. Evolution of the magnetic field, current density and temperature for three values of the initial plasma β. Right most column: temperature dependence of the resistivity is turned off. x-axis in units of the initial width of the current sheet, y-axis in units of the initial resistive time. Radiative cooling is not included. Taken from [12].

when all the potassium becomes ionized. This leads to temperatures well above 2000 K, which are necessary for Type B CAIs [15] and barred olivine textures [16].

4 Conclusions

There is an interesting instability in MHD resistive dissipation which occurs when the conductivity is an adequately strongly increasing function of temperature, which behave like a short circuit, concentrating the current and the resistive energy dissipation. This instability is active in protoplanetary disks (among other locations) when thermal ionization of alkali metals is the dominant source of free electrons, and is well suited to processing minerals at high temperatures as seen in chondritic meteorites. As a further complication however, while this instability increases the local energy dissipation rate, it reduces the global dissipation rate for a given current sheet. For the MRI to drive an accretion flow, it must dissipate the magnetic energy before the field becomes too strong which itself shuts off the MRI. Understanding how the MRI behaves in the presence of the short circuit instability will be an important step in understanding the nature and evolution of protoplanetary disks.

References

[1] Balbus, S. A., & Hawley, J. F., The Astrophysical Journal **376**, 214-233 (1991)

[2] Alexander, C. M. O., Boss, A. P., & Carlson, R. W., Science 2001, Science **293**, 64-69 (2001)

[3] Connolly, H. C., Jr., Jones, B. D., & Hewins, R. H., Geochimica et Cosmochimica Acta **62**, 2725-2735 (1998)

[4] Bland, P. A., Alard, O., Benedix, G. K., et al., Proceedings of the National Academy of Science **102**, 13755-13760 (2005)

[5] Hezel, D. C., & Palme, H., Earth and Planetary Science Letters **265**, 716-725 (2008)

[6] Alexander, C. M. O., Russell, S. S., Arden, J. W., et al., Meteoritics and Planetary Science **33**, 603-622 (1998)

[7] Huss, G. R., & Lewis, R. S., Meteoritics **29**, 811-829 (1994)

[8] Mendybaev, R. A., Beckett, J. R., Grossman, L., et al., Geochimica et Cosmochimica Acta **66**, 661-682 (2002)

[9] Ebel, D. S., Weisberg, M. K., Hertz, J., & Campbell, A. J., Meteoritics and Planetary Science **43**, 1725-1740 (2008)

[10] Krot, A. N., & Wasson, J. T., Geochimica et Cosmochimica Acta **59**, 4951-4966 (1995)

[11] Cowley, S. C., Longcope, D. W., & Sudan, R. N., Physics Reports **283**, 227-251 (1997)

[12] Hubbard, A., McNally, C. P., & Mac Low, M.-M., The Astrophysical Journal **761**, 10 pp. (2012)

[13] McNally, C. P., Hubbard, A., Mac Low, M.-M., Ebel, D. S., & D'Alessio, P., arXiv:1301.1698 (2013)

[14] Sargent, B. A., Forrest, W. J., Tayrien, C., et al., The Astrophysical Journal Supplement **182**, 477-508 (2009)

[15] Grossman, L., Ebel, D. S., Simon, S. B., et al., Geochimica et Cosmochimica Acta **64**, 2879-2894 (2000)

[16] Connolly, H. C., Jr., Desch, S. J., Ash, R. D., & Jones, R. H., *Meteorites and the Early Solar System II* (University of Arizona Press, Tucson 2006) 383-397