Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
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Magnetic fields, stellar feedback, and the geometry of H II regions

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Abstract. Magnetic pressure has long been known to dominate over gas pressure in atomic and molecular regions of the interstellar medium. Here I review several recent observational studies of the relationships between the H^+, H^0 and H_2 regions in M42 (the Orion complex) and M17. A simple picture results. When stars form they push back surrounding material, mainly through the outward momentum of starlight acting on grains, and field lines are dragged with the gas due to flux freezing. The magnetic field is compressed and the magnetic pressure increases until it is able to resist further expansion and the system comes into approximate magnetostatic equilibrium. Magnetic field lines can be preferentially aligned perpendicular to the long axis of quiescent cloud before stars form. After star formation and pushback occurs ionized gas will be constrained to flow along field lines and escape from the system along directions perpendicular to the long axis. The magnetic field may play other roles in the physics of the H II region and associated PDR. Cosmic rays may be enhanced along with the field and provide additional heating of atomic and molecular material. Wave motions may be associated with the field and contribute a component of turbulence to observed line profiles.

Keywords. ISM: magnetic fields – HII regions – ISM: individual (M17,M42) – cosmic rays – ISM: molecules

1. Introduction – The magnetic field of a quiescent cloud

Magnetic fields play pivotal roles in star-forming environments. Many aspects of this rich topic are covered in other papers in this book, and the review by Heiles & Crutcher (2005) is essential reading.

The first of the many influences of the field is in the formation of the molecular cloud itself. The crucial physics is the coupling between the magnetic field and even weakly ionized gas. This so-called flux freezing means that there is a relationship, set by the geometry of any expansion or contraction that occurs, between the gas and field density. This means that while gas is free to move along field lines, gas motions perpendicular to the field will magnify or weaken the field.

Figure 1, taken from Heiles (1988), shows the dark cloud L204. The orientation of the magnetic field, as deduced from starlight linear polarization, is indicated by the black lines. Field lines tend to lie perpendicular to the long axis of the filament. The Pipe Nebula (Alves *et al.* 2008) is another example. This geometry is not uncommon (Heiles & Troland 2005). One interpretation is that the field is strong enough to guide contraction along field lines so that clouds tend to form as sheets or filaments (Heitsch, Stone & Hartmann 2009). Gravitational contraction along the filament may further strengthen the field.

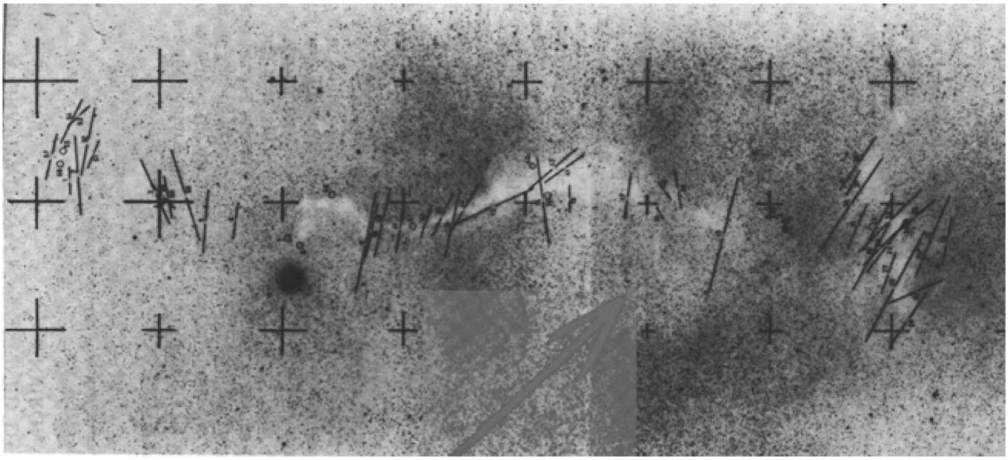

Figure 1. Figure 1, from Heiles (1988), showing the dark cloud Lynds 204. Magnetic field lines, shown as black lines, line roughly orthogonal to the long axis of the filament.

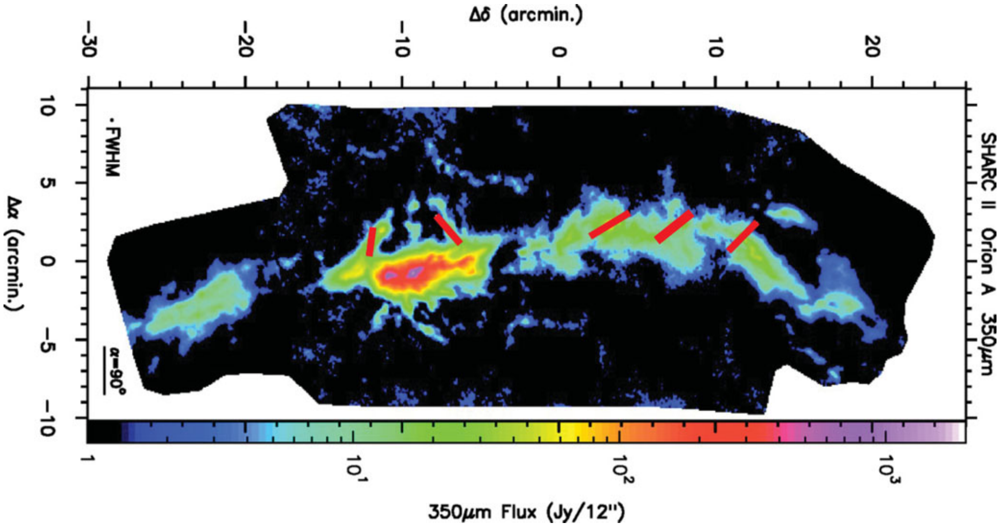

Figure 2. The Orion Molecular Cloud as imaged at 350μm by Houde *et al.* (2004). The figure has been rotated so that north is to the right. The red lines show the direction of the magnetic field deduced from the linearly polarized dust emission. The Trapezium cluster is centered on the bright region to the left.

2. Orion - an active star-forming region

The Orion complex is more complicated because of the feedback associated with active star formation. Figure 2, taken from Houde *et al.* (2004), shows the geometry of the field as revealed by linearly polarized dust emission. The surface brightness of the $\lambda 350\mu$m thermal emission is shown by the colored scale. The red lines indicate the deduced field direction. The bright region to left of center is warm dust in molecular material surrounding the Trapezium cluster. Active star formation and associated starlight cause the dust to be radiatively heated and glow brightly near the young stars.

The field lines tend to lie perpendicular to the long axis of the molecular cloud in the relatively quiescent northern regions. This is reminiscent of the geometry of Lynds 204 shown in Figure 1.

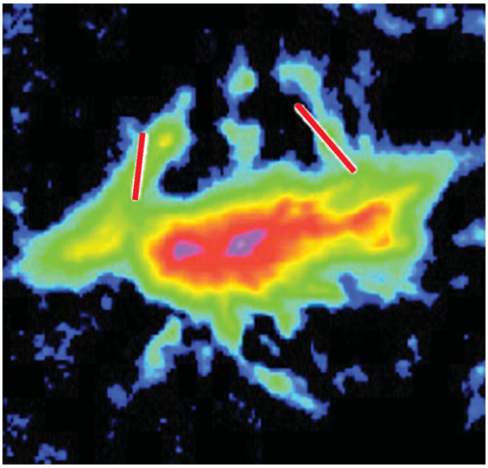

Figure 3. A zoom into Figure 2 from Houde *et al* (2004) showing emission from the parent molecular cloud in the region around the Trapezium cluster. The orientation of the image is the same as in Figure 2. The orientation of the magnetic field is indicated by the red lines.

The region surrounding the Trapezium is more complicated due to the presence of massive stars and their associated radiation pressure. Figure 3 shows a zoom of the region near the Trapezium. Here the field lines tend to lie perpendicular to the line between the point and the Trapezium.

This review centers on the relationships between stars and the surrounding H^+, H^0, and H_2 layers, the so-called H II region, PDR, and molecular cloud. Figure 4 shows the geometry of the regions near the young star cluster and bright H II region in the Orion complex. This is adopted from Osterbrock & Ferland (2006).

Feedback from Trapezium cluster has strongly affected the cloud geometry. Stellar winds and associated shocks produce a bubble of hot gas that has recently been detected in the X-rays (Güdel *et al.* 2007). A combination of thermal gas pressure and starlight momentum pushes cooler gas away from the star cluster and results in the blister geometry shown in Figure 4.

Most of the extinction seen in the HST image of the Orion H II Region arises in the Veil, the layer of predominantly atomic gas that lies on this side of the hot bubble (O'Dell 2001a). The Veil has been extensively studied at H I 21 cm. The thermal continuum emission produced by the H^+ region is used to probe the Veil, where atomic gas produces a 21 cm absorption line. Zeeman measurements of the line of sight magnetic field show it to be surprisingly strong, approaching 50 μG, roughly 1 dex stronger than the field in the diffuse ISM (Troland *et al.* 1989). Why is the field so strong?

Abel *et al.* (2004; 2006) combined optical and UV measurements of absorption lines formed in the Veil to derive its density, kinetic temperature (and so its gas pressure) and its distance from the Trapezium. They found that magnetic pressure greatly exceeded the gas pressure, as is typical of the ISM, and that the magnetic pressure exceeded even the turbulent pressure in one of the two Veil components. The Veil is a thin sheet which we view roughly face on.

3. M17 and magnetostatic equilibrium

The M17 star-forming region is much larger and more luminous than Orion but also much further away. Similar Zeeman polarization measurements of the magnetic field in

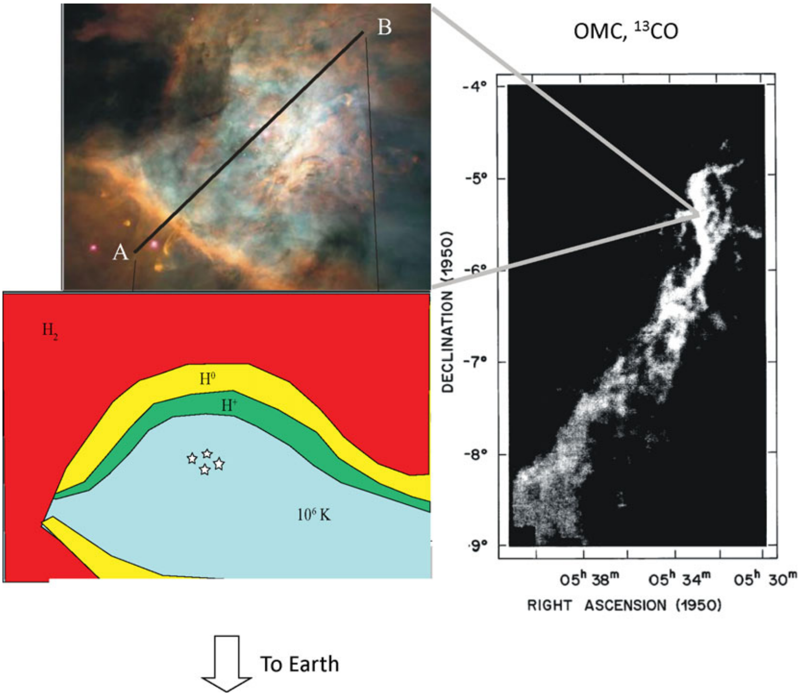

Figure 4. The geometry of the Orion H II region, PDR, and molecular cloud. This Figure, adopted from Osterbrock & Ferland (2006), shows a CO image of the molecular cloud to the right and a zoom into the HST image of the H II region at upper left. The geometry of the cut shown as the black line from A to B in the HST image is shown in the lower left panel. The star cluster is surrounded by hot gas produced by stellar winds. The bright H II region is mainly an ionized layer on the surface of the background molecular cloud. Much of the extinction visible in the HST image arises in Orion's "Veil", the layer of predominantly atomic gas that lies on the near side of the star cluster. The Veil is the region where H I 21 cm circular polarization measures the line-of-sight magnetic field.

the atomic hydrogen region have been performed (Brogan & Troland 2001) and an even stronger field, approaching 700 μG, was found.

Pellegrini *et al* (2007 hereafter P07) combined a broad range of spectral observations to make a coherent picture of the geometry of M17. M17 has an overall geometry that is similar to Orion, but viewed from a a different angle, as shown in Figure 5. Some of these ideas are further outlined in Ferland (2008). The ionizing star cluster and the intrinsically brightest part of the H II region are hidden behind a layer of atomic and molecular gas. The Zeeman magnetic field is stronger in the regions to the right (West) of the star cluster then along directions more towards the cluster.

P07 showed that the H^+ H^0 and H_2 layers were in a state of quasi-magnetostatic equilibrium. The outward force of starlight, mainly ionizing radiation acting on gas and dust, is resisted by the magnetic pressure in deeper regions of the cloud. The picture they proposed is that the combination of thermal gas pressure from the hot bubble and radiation pressure due to starlight has pushed back surrounding gas, strengthening the magnetic field, until the magnetic pressure could resist further compression.

The gas pressure in the hot wind-blown bubble is close to the pressure near the illuminated face of the H II Region. The absorption of the outward-flowing starlight pushes the H II region away from the cluster increasing the gas density and magnetic pressure.

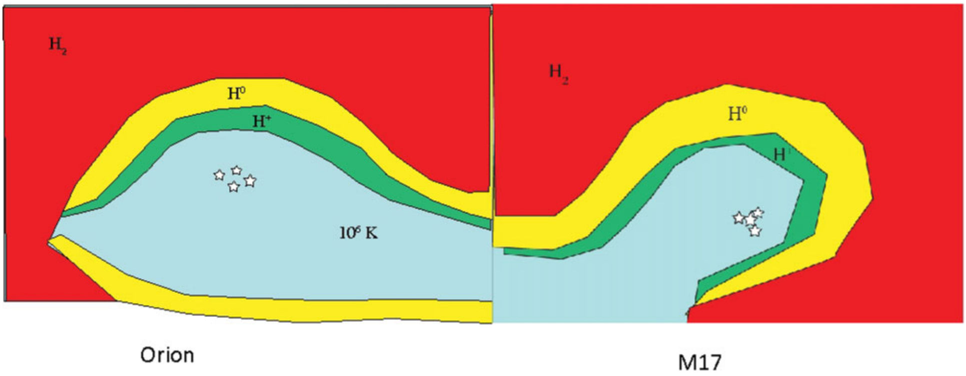

Figure 5. A comparison of the geometry of Orion (left) and M17 (right). This is not drawn to scale - M17 is roughly 1 dex larger than Orion. We view both geometries from the bottom looking up. The atomic layer in front of the star cluster and H II region is translucent in Orion. In M17 the layer has a large extinction and has atomic, ionized, and molecular constituents. The Zeeman magnetic field measurements use the emission of the H^+ layer as the continuum source. The radio absorption measurements probe the line of sight component of the magnetic field in the H^0 layer between the observer and the H^+ region.

The magnetic pressure increases as the square of the field, so for many geometries the magnetic pressure will increase faster than the gas pressure. Most starlight is absorbed by the outermost parts of the H_2 layer due to the large dust extinction. Magnetic pressure dominates at this point so the total luminosity of the star cluster and the magnetic field at this point are related.

P07 gave a simple relationship between the total luminosity of the star cluster and the magnetic pressure in deeper regions of the cloud. In this picture the strong magnetic fields associated with active regions of star formation are directly related to the luminosity of the central stars. This provides a natural explanation for why strong fields are found near star-forming regions.

4. The magnetic field and the geometry of the M17 H II region

The linear polarization measurements (Figures 1 & 2) suggest that the magnetic field may be roughly perpendicular to the axis of a filamentary molecular cloud. What happens when star formation occurs in such a geometry? Two forces act to guide the resulting expansion of the ionized gas.

The first is the effects of an ordered magnetic field as shown in Figure 6. The left panel shows a segment of a filamentary molecular cloud with an ordered field. The right panel shows the expanded hot bubble and compressed field lines. The magnetic field increases perpendicular to the “equator” of the cloud. Expansion can be halted by the field in this direction. There is no increase along the “poles” and gas may be free to move in this direction.

Figure 7 shows a composite image of the Orion molecular cloud, star cluster, and H II Region. An image with higher resolution data is given in Henney (2008). Figure 7 shows that the visible H II region opens in the direction below the molecular cloud in the image. This is the direction where the X-ray emission discovered by Güdel *et al.* (2008) occurs and is the likely direction of outflow of the hot gas. The geometry of the magnetic field shown in Figure 6 may account for the direction of the extended optical emission since gas will only be free to move in directions perpendicular to the filament.

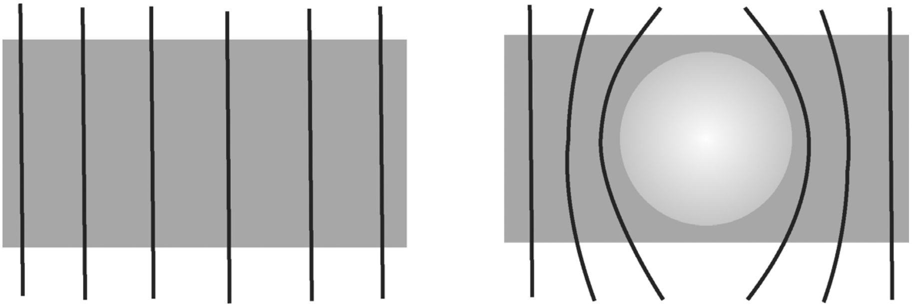

Figure 6. A cartoon showing the expansion of an H II region into an ordered magnetic field. The left panel shows a quiescent cloud with the field lines orthogonal to the axis of the cloud. The right panel shows the expanded ionized gas with associated changes in the field geometry.

Linear polarization shows the direction of the magnetic field. Figure 3, which is a zoom into a portion of the larger map given in Figure 2, suggests that the field lines near the Trapezium are roughly orthogonal to the direction towards the star cluster. This field geometry is consistent with the picture shown in Figure 6.

Zeeman circular polarization measurements detect the line of sight component of the magnetic field. For the geometry shown in Figure 6 observations in the direction of the star cluster along the equator of the slab will detect the smallest field. The line-of-sight field should increase as the telescope beam moves away from the cluster and the impact parameter of the passing ray increases. This is the general sense of the measured magnetic field of Orion and M17. The magnetic field tends to be stronger in directions that do not center on the star cluster. But the field does not go to zero in the direction of the cluster in Orion. (Measurements do not exist in this direction in M17.) This may indicate that the field has a disorganized component in addition to the ordered component detected by linear polarization.

The mass shaping due to the large mass of the molecular cloud is a second effect influencing the expansion of the H II region. In both Orion and M17 star formation appears to have occurred near a surface of the molecular cloud and expanding x-ray emitting gas is freely expanding out into the general ISM along along an open path. There is relatively little material along our line of sight to the Trapezium while the main outflow appears to be towards the Southwest (towards the bottom in Figure 7). In M17 there is a large column density of material along our line of sight towards the cluster, which is optically obscured, while the outflowing hot gas is directed towards the East (to the left in the right panel of Figure 5). In both cases a large mass of molecular gas is present in some directions but not in others. This mass shaping must also affect the geometry of the ionized bubble.

5. Are cosmic rays amplified as well?

Cosmic rays are in approximate energy equipartition with the magnetic field in the diffuse ISM (Webber 1998). Energy equipartition is usually assumed when observations of radio synchrotron emission are interpreted in terms of a cosmic ray density or magnetic field, as reviewed in other papers in this volume. Such equipartition does not occur because of any direct microphysical coupling between the energy reservoirs in the environment. Rather it is a minimum energy configuration that can be established if the system exists for a long enough time to have become relaxed. The equipartition value of the cosmic ray density does provide a reference point to which I will come back below.

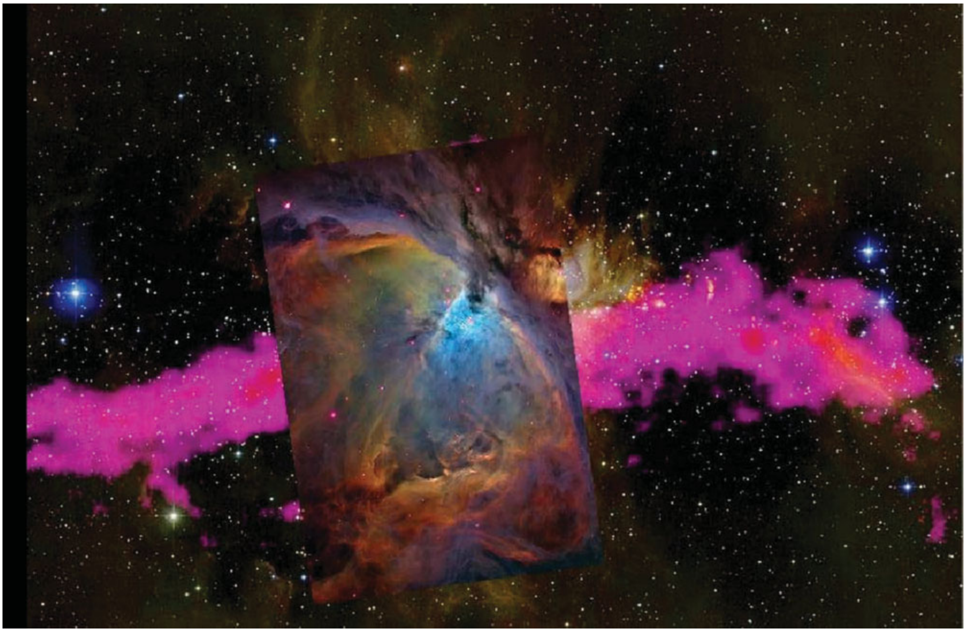

Figure 7. William J. Henney's composite of an optical image of the Orion H II region in the center and a radio image showing the distribution of carbon monoxide molecules in red. Optical image obtained as part of the Two Micron All Sky Survey (2MASS), a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. The CO image is derived from Plume *et al.*(2000). The x-ray emission, which is not shown, occurs below the "fan" of optical emission which points below the molecular cloud.

Low-energy cosmic ray electrons are strongly trapped by the magnetic field because their gyro radius is much smaller than the physical scales of the molecular cloud or H II region. The compression of field lines shown in Figure 6 will also increase the cosmic ray density. Cosmic rays will be free to drift along field lines unless their pitch angle is perfectly aligned with the field. They should drift out of the environment relatively quickly. This drift would be inhibited if the field has a disorganized component. Low-energy cosmic rays can be locally enhanced by MHD waves (Padoan & Scalo 2005) so spatial variations are expected. This is clearly a complicated topic.

The galactic cosmic ray density is usually derived from observations of the ion chemistry (Spitzer 1978). Recent observations of the fraction of gas in H_3^+ along a number of sight lines suggest that the galactic background cosmic ray ionization rate has been underestimated by about 1 dex, and that this rate varies from one sight line to another (Indriolo *et al.* 2007). This shows that the cosmic ray density of even quiescent regions is open to question.

Cosmic rays both heat and ionize gas. The proportion of energy that goes into heating or ionization is determined by the degree of ionization of the gas (Osterbrock & Ferland 2006). Heating by cosmic rays is not insignificant in atomic regions even with the old lower background rate (Tielens & Hollenbach 1985). If the cosmic ray rates are significantly higher than previously thought then they will be even more important in heating atomic and molecular regions.

Giammanco & Beckman (2005) proposed that a high flux of cosmic rays may explain the "temperature fluctuations" problem in H II regions. The basic conundrum is that different measures of the kinetic temperature in the ionized gas do not agree with one another. The disagreement is systematic and suggests that a range of kinetic temperatures is present. It is hard to understand how this can occur due to the rapid increase of the gas cooling function with increasing temperature (Ferland 2003) and the fact that a Boltzmann distribution is established so quickly in an ionized gas (Spitzer 1978). Giammanco & Beckman argue that the supplemental heating provided by enhanced cosmic rays would produce the observed effects.

Orion's "Bar", a linear feature obvious on most optical images of the H II region (O'Dell 2001a), is thought to be an escarpment on the surface of the background molecular cloud. Ionizing radiation from the Trapezium strikes the Bar in such a way that we can observe the transition between H^+ H^0 and H_2 regions nearly edge on. Because of its special geometry, the Bar has become a decisive test for the physics of the interface between molecular and ionized regions.

Pellegrini *et al.* (2008) and Shaw *et al.* (2009) studied spectral variations across the Bar with the goal of reproducing the observed emission profiles of various tracers of ionized, atomic, and molecular gas. They found that cosmic rays in equipartition with the observed strong magnetic field reproduced the observations. P08 also required an enhanced flux of cosmic rays to account for the atomic and molecular emission in Orion.

6. Magnetic fields and non-thermal line widths

ISM spectral lines, both emission and absorption, are usually found to have widths too large to be due to purely thermal motions. These non-thermal line widths were often interpreted as a form of non-dissipative wave motion with the kinetic and magnetic energies in rough energy equipartition. Numerical MHD simulations suggest that such waves should be damped, which then requires that some energy source drive them, but in any case the turbulently broadened lines can be taken as empirically motivated. Heiles & Crutcher (2005) review the situation.

It is successively more difficult to measure non-thermal line widths in PDRs and H II regions than in molecular clouds due to the increasing temperature and decreasing mass per particle. A given turbulent motion, which might be associated with a particular magnetic field, is a smaller fraction of the thermal line width in hot ionized gas than it would be in a cold molecular medium. Non-thermal line widths are seen in the spectra of the H II regions and PDRs. PDR lines have long been known to be turbulently broadened (Tielens & Hollenbach 1985) and Roshi (2007) has recently suggested that non-thermal line widths of carbon radio recombination lines, which should form in the PDR, may be associated with MHD waves.

Optical emission lines from the H II region also have larger-than-expected line widths. These widths are observed to scale with the luminosity of the star cluster and have been studied extensively because of their possible use as a standard candle (Melnick *et al.* 1988). For low-luminosity objects like Orion the observation is difficult because the expansion of the ionized gas away from the molecular cloud, which occurs at roughly the speed of sound in the H II region ($\sim 10\,\mathrm{km\,s^{-1}}$), is similar to the turbulent speed. However, very careful studies have been done (O'Dell *et al* 2005; García-Díaz et a. 2008) and find a significant component of turbulence. There is no agreed-upon model for the origin of the turbulence seen in the optical lines but MHD waves are a possibility (Ferland 2001; O'Dell 2001a, 2001b). This is important because the turbulent energy is a significant part of the energy budget in Orion. If this turbulence is dissipative, as suggested by numerical MHD simulations, then it would act to heat the gas (Pan & Padoan 2008).

Line widths in excess of 100 km s^{-1} can be found in luminous extragalactic H II regions. Beckman & Relaño (2004) argue that these line widths may be due to MHD effects associated with the magnetic field. This would imply that relationships between magnetic field, turbulent, and gravitational energies extend over many orders of magnitude of mass. Again, if the waves are dissipative then, depending on the damping timescale, they may constitute a significant heating source.

7. Conclusions

(1) A number of studies of the H^+, H^0 / H_2 regions of active star-forming regions, chosen to have high-quality Zeeman 21 cm detections of the magnetic field in the H^0 region, have been conducted. In both Orion's Veil and the H^0 region along the line of sight to the H^+ region in M17 the magnetic pressure is much greater than the gas pressure, as is commonly found in the ISM. The magnetic pressure exceeds the turbulent pressure in one component of the Veil.

(2) The strongest magnetic fields in diffuse gas are found near regions of active star formation. The field in the atomic hydrogen region of M17, $\sim 700\mu$G, is among the strongest observed. This corresponds to a magnetic pressure roughly 3 dex larger than is found in the diffuse ISM.

(3) Simulations of the emission-line spectra of the H^+, H^0 / H_2 regions in M17 which reproduce the observed magnetic field show that the geometry is approximately in magnetostatic equilibrium. The outward radiation pressure due to starlight is balanced by the magnetic pressure in well-shielded regions of the cloud. This accounts for the large field that is observed.

(4) Linear polarization studies suggest that the field is often oriented perpendicular to the long axis of filamentary clouds. This may be the result of the magnetic field guiding the formation of the cloud or of the subsequent gravitational contraction along the filament (Heitsch *et al.* 2009).

(5) Cosmic rays are found to be in energy equipartition with the magnetic field in the diffuse ISM, and equipartition is often assumed to hold for synchrotron emitting regions. Cosmic rays both heat and ionize atomic and molecular gas. If cosmic rays are enhanced along with the field then they would constitute an important heating source for atomic and molecular regions.

(6) Non-thermal line widths are often found in emission line spectra of star-forming regions. Several recent studies have suggested that these may be due to MHD waves associated with the magnetic field. If the waves are dissipative then this would constitute a gas heating mechanism.

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