

## 1 Astrophysical plasmas we'll meet

We will be using several different astrophysical systems as examples of plasma astrophysics. While you've probably run into all of these before, it may be worth collecting a brief description of them in one place. For some objects I'll put in "typical" parameters (size, density, temperature, etc); for others, such numbers are hard to pin down, & we'll introduce them as needed later on.

### The terrestrial ionosphere and magnetosphere

Start at the surface of the earth: the atmosphere you're breathing, as you read this, is very close to charge neutral. The density of electrons is only  $\sim 10 - 100 \text{ cm}^{-3}$  (how does this compare to the total number density of the low-altitude atmosphere?). But this changes when you get to altitudes  $\gtrsim 100 \text{ km}$ . The ionized fraction, and total ionized number density, grows suddenly (due to what? what ionizes the upper atmosphere?), until at a few hundred km you reach the highly ionized *ionosphere*. The number density here  $\sim 10^6 \text{ cm}^{-3}$  (but remember this changes rapidly with height, due to the exponential density of the atmosphere); the temperature  $\sim 10^3 \text{ K}$ . This is our nearest-by example of an astrophysical plasma; we see its signature in the propagation, bending (refraction) or non-transmission of radio waves.

Continuing upwards, the ionospheric density drops off more rapidly than does the earth's magnetic field (which is a dipole field,  $\sim 1 \text{ G}$  at the earth's surface). Thus you reach the *magnetosphere*, a region where the plasma density is small and the plasma is dominated dynamically by MHD and plasma effects. On the sunward side of the planet, the magnetopause extends to several earth radii, and is bounded by the bow shock where the solar wind runs into the earth's B field. On the "downstream" (antisunward) side of the planet, the magnetotail extends to several tens of  $R_E$ .

**The solar corona and solar wind** Now, start at the sun's surface and move outward ... the *photosphere* is the visible "surface" of the sun, with  $T \simeq 5800 \text{ K}$ . It's about 500 km thick, mostly neutral. We know a good bit about magnetic fields here, because we can observe sunspots & related phenomena. The mean field  $B \sim 1 \text{ G}$ ; sunspot fields are  $\sim 1 \text{ kG}$ . The *chromosphere* is a region 2000-3000 km thick, just above the photo-

sphere. Going upwards, the temperature first drops to  $\sim 4000 \text{ K}$ , then rises to  $\sim 10^4 \text{ K}$ ; the density drops rapidly, from  $\gtrsim 10^{15} \text{ cm}^{-3}$  at the base to  $\sim 10^9 \text{ cm}^{-3}$  at the top. Above this is the *corona*, in which the temperature rises abruptly to  $\gtrsim 10^6 \text{ K}$ , and the density continues to drop (but more gently). Magnetic fields are "outlined" by the beautiful filaments and prominences which extend from the chromosphere up into the corona. These structures have typical thicknesses  $\sim 6000 \text{ km}$ , lengths  $\sim 100,000 \text{ km}$ , and extend to  $\sim 50,000 \text{ km}$  above the surface. The plasma in a quiescent prominence is about 300 times colder and denser than the surrounding coronal gas;  $B \sim 10 \text{ G}$  is usually quoted as typical.

The corona is also the source of the *solar wind*. The outflow starts in coronal holes, large open regions (visible in X-ray images) that are associated with "open" B field lines and high-speed solar wind streams. Solar wind numbers are of course a function of radius. At the earth, the wind density  $\sim 10 \text{ cm}^{-3}$ ,  $T \sim 10^5 \text{ K}$ ,  $B \sim 10^{-4} \text{ G}$ , and the wind is very supersonic, with  $v \sim 500 \text{ km/s}$ . Elsewhere in the wind, the velocity changes only slowly,  $v^2 \propto \ln r$ , and we think the temperature doesn't change by much; the behavior of the other parameters (density, field, pressure) is set by conservation laws.

**Stars** You know stars are held together by gravity, and supported against collapse by their internal pressure. They are the classic example of *hydrostatic equilibrium*, which we'll work with later in the course. In addition, stars are almost totally ionized (how do you know? What's the temperature, interior and surface, of your favorite mass of star?), and thus are plasmas. We also know that stars are magnetized; we measure the sun's surface B field directly, and that of other stars indirectly (through X-ray and radio observations of stellar flares, for instance). That means that *magnetohydrodynamic* (MHD) effects – the forces exerted by the B fields and the currents which support them – must be considered. We won't talk a lot about "normal" stars in this course, but you should remember that MHD effects are important to many aspects of their formation and evolution.

**HII regions** Put a hot young star down in a region of neutral ISM. If the star is hot enough – if it produces a substantial amount of UV photons (with  $h\nu > 13.6$

eV) – it will photoionize the nearby ISM, making an HII region. These vary a lot across the galaxy in their density and size. The spectrum ranges from young, ultra-compact ones, with diameter  $< 0.03$  pc and density  $> 10^4 \text{ cm}^{-3}$  (which are hidden behind thick dust clouds, so that you can only see them with radio or IR); to the older, big, bright, famous ones, which have blown off their dust shrouds and are beautiful optical sources (such as the Orion nebula; diameter  $\sim 1$  pc, very inhomogeneous, but maybe it has a typical density  $\sim 10^3 \text{ cm}^{-3}$ ). The temperature of a photoionized region is regulated by the microphysics:  $T \lesssim 10^4 \text{ K}$  always (see Physics 426 for the proof).

**Supernova remnants** The physical picture is easy to describe: a star goes bang, and ejects a rapidly moving shell of matter. This shell moves out into the local interstellar medium (or the wind ejected by the pre-SN star), pushing the ambient matter ahead of it and decelerating as it goes. We'll talk about SNR in more detail next term; for now, typical sizes are a few pc (with older ones being bigger, of course). Typical densities and temperatures are harder ... the outer shell is defined by a shock, and the conditions therein are complex. Inside of the shell, the shocked gas is hot,  $\sim 10^7 \text{ K}$  – we see it in X-rays.

Another type of SNR, about 10% of the population, is a *filled remnant*, also called a *plerion* or *pulsar wind nebula*. These are the remnants with active pulsars inside; the relativistic-plasma wind from the pulsar fills the SNR. The Crab nebula is a well-known example of this.

**Our galaxy & the interstellar medium** Our galaxy is a typical big spiral. It is rotation supported in the plane (stars + gas in circular orbits) and supported by “heat” (*i.e.*, random motions) transverse to the plane. The stellar disk extends  $\sim 15$  kpc from the center, with the sun at 8.5 kpc out; the gas disk in a typical spiral extends much further, out to  $\sim 30 - 50$  kpc. The disk thickness depends a bit on which species you measure (stars, hot gas, cool gas ..); typically it's  $\sim 1/2$  kpc thick.

The diffuse interstellar medium (ISM) is multiphase: there is a cold, neutral component; a “warm”, mostly ionized component; and a hot (“coronal gas”) component. As everywhere in diffuse astrophysical plasmas, the chemical composition is almost all hydrogen; all

heavier elements contribute no more than a few per cent. Each of these phases has a range of temperatures and densities. For “typical” numbers, let's say the cold, neutral HI is at  $n \sim 1 \text{ cm}^{-3}$  and  $T \sim 100 \text{ K}$ ; the warm, partly ionized HII is at  $n \sim 0.2 \text{ cm}^{-3}$  and  $T \sim 6000 \text{ K}$ ; and the coronal gas is at  $n \sim 10^{-2} \text{ cm}^{-3}$  and  $T \sim 10^6 \text{ K}$ . Note that each of these phases are in approximate pressure balance:  $p = nk_B T$  is about the same for each. Measured as an energy density each phase is at  $\sim 1 \text{ eV/cm}^3$ . The ISM is of course magnetized, and also contains an energetically important relativistic plasma (the cosmic rays); each of these is also at  $\sim 1 \text{ eV/cm}^3$ .

The galaxy also has a hot, extended halo. We detect it mostly through its synchrotron emission (from relativistic particles undergoing gyromotion in the local magnetic field). Based on other galaxies, our halo probably extends a few kpc above and below the plane; information on its composition (thermal gas, B field, energy density, etc) is harder to come by.

**Cosmic rays** These are worth their own paragraph. Most of the ISM is “thermal” – that is it has a well-defined temperature (subrelativistic:  $kT \ll mc^2$ ) and a Maxwellian distribution of the particle velocities. However it also contains a component of highly energetic ( $E = \gamma mc^2$ ; the Lorentz factor  $\gamma \gg 1$ ) charged particles. These particles are accelerated “somewhere” in or out of the galaxy and remain tied to B field lines as they move through the ISM. They are “nonthermal”: their energy/velocity distribution is not a Maxwellian, rather a power law (which means they haven't had time to thermalize *via* collisions with the ISM. Their lowest energy  $\sim 10^{11} \text{ eV}$  (at least the lowest that we detect); their highest energy  $\sim 10^{20} - 10^{21} \text{ eV}$ .

**Elliptical galaxies** These are the big round ones. Sizes: they typically have an inner core, radius  $\sim 1 - 2$  kpc, and an extended, power-law outer halo (in which the stellar density  $\propto 1/r^x$ , where  $x \sim 2 - 3$ ). They are supported by the random motions of their stars; they show little or no organized rotation. It used to be thought that they had no ISM, because you couldn't see it in optical pictures, and because they show little ongoing star formation; we now know that's wrong. Their ISM is mostly hot,  $T \sim 10^7 \text{ K}$  (we see it with X-ray telescopes) – so it's less inclined to star formation than the cooler, denser ISM in a spiral galaxy. Its

density distribution is roughly similar to that of the stars; the density  $\sim 0.1 \text{ cm}^{-3}$  in the core, and falls off roughly as a power law outside the core.

Ellipticals do, however, contain a smaller amount of cooler ISM, which can be detected with radio and millimeter-wave telescopes. It stands to reason – by analogy with spiral galaxies and clusters of galaxies – that the ISM in an elliptical should also be magnetized and contain a relativistic plasma component. There has been very little observational work on this question, so I can't offer any numbers for the field or the cosmic rays here.

**Radio jets and radio galaxies** Let matter accrete onto a compact object (which could be the core of a protostar, or a neutron star, or a black hole). Some part of the accreted matter and energy is driven away, into an outflow – which in some (many) cases can be highly collimated. The outflowing plasma is very often (probably always) magnetized, and it often contains a relativistic particle component which we see in radio frequencies through its synchrotron radiation. These are thus called *radio jets*. Their size varies from AU (protostellar jets) to a few pc (jets from galactic accretion sources) to 100's of kpc (jets from supermassive black holes in active galaxies). Their internal state (density, temperature, composition) also varies a lot between these different objects. What they have in common is that they all involve energetic, relativistic plasma which is controlled dynamically by MHD effects.

**Clusters of galaxies** These are the largest self-gravitating structures in the universe. Their structure is sort of like a big elliptical galaxy, with an inner core, radius  $\sim 300 - 500 \text{ kpc}$ , and an outer halo where density (of gas or galaxies) decays roughly as a power law. The outer halo can be traced to a radius of more than a Mpc in big clusters. The cluster has a plasma atmosphere – the *intracluster medium*, ICM. It is composed partly of primordial material which accumulated as the cluster formed, and partly of processed material that has been through star formation in the galaxies and then ejected back into the ICM. Typical temperatures,  $\sim 10^8 \text{ K}$ ; typical densities  $\sim 10^{-3} \text{ cm}^{-3}$  in the core (and again decaying outwards).

We are beginning to learn that the ICM is magnetized, and that it also contains a relativistic (“cosmic ray”)

component. Numbers here are not yet well determined. A “typical” field seems to be  $B \lesssim \mu\text{G}$ , but  $B$  can reach tens of  $\mu\text{G}$  in high field regions. The mean cosmic ray energy density might be  $\sim 1 - 10\%$  of the thermal plasma pressure.

**What's left?** Here's a question for the student: what astrophysical objects have I *not* mentioned? How many objects can you think of that are neither plasmas nor affected somehow by MHD effects?

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### Key points

After each chapter I'll try to highlight the most important issues in that chapter. Here, it's just the objects themselves: you should be familiar with the range of astrophysical plasmas we'll encounter, including typical sizes, densities, *etc* for each one.