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Hydrogen in strong magnetic fields in neutron star surfaces

Edwin E Salpeter

Space Sciences Building, Cornell University, Ithaca, NY 14853, USA

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Abstract. In magnetic fields of very much more than 2×10^9 G, polyatomic hydrogen molecules, in the form of long chains, are stable. In neutron star surfaces, fields of 10^{13} G are commonplace and 10^{15} G has been reported. Liquid hydrogen can form at the higher field with a zero-pressure density of about 10^6 g cm^{-3}. At these densities, hydrogen can burn to helium by pycnonuclear reactions even at low temperatures—the 'real cold fusion'.

1. Introduction

The first neutron stars which were encountered observationally were radio pulsars. These are isolated, spinning neutron stars where rotational energy is converted into electromagnetic radiation. This emitted radiation is likely to be accompanied by a little mass loss, so the chemical composition of the surface reflects the equilibrium composition of layers a little deeper inside the star—typically iron. We will not discuss these 'inside-out' neutron stars, but only the 'outside-in' ones, where mass is accreted from the outside onto the neutron star surface. The infalling matter comes either from interstellar gas or from the atmosphere of an ordinary companion star and therefore consists mainly of hydrogen and helium.

The luminosity of an accreting neutron star depends on the rate of accretion, which can vary enormously from case-to-case, for example 10^{-4} to 10^4 solar luminosities. The corresponding temperature T_{ph} of the photosphere (the layer in the atmosphere from which photons escape with fairly little scattering) ranges from about 10^5 K to a little above 10^7 K. Until a few years ago, x-ray telescopes were not sensitive to soft x-rays and only the brightest and hottest surfaces were observed. As the hydrogen and helium flows a little deeper in, thermonuclear reactions are ignited and very complex explosions and instabilities are observed [1]. After discussing the thermal equilibrium of various phases of hydrogen in very strong magnetic fields, we will return to slow accretion where T_{ph} is only 10^6 K or a little less. The hydrogen burning, which is possible in strong fields even at 'low' temperatures, will be of special interest.

The value of the magnetic field strength B in the atmosphere of a neutron star can be measured or inferred by various methods. B varies greatly from case to case and the best measured values are in 'the middle of the range' of about 10^{12} G to 2×10^{13} G. Such fields are rather weak for a neutron star—fields of order 10^{17} G would be needed for the total magnetic energy of the star to equal the gravitational energy. Recently, some surface fields of almost 10^{15} G have been reported [2]. The liquid phase of hydrogen, discussed in section 3, is relevant for such large fields. We give a few references here, but more will be found in the paper on which this talk is based [3].

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2. Hydrogen atoms and long chain molecules

For hydrogen the atomic unit B_0 for field strength and a dimensionless parameter b are $b = B/B_0$, $B_0 = 2.35 \times 10^9$ G. We assume throughout that $b \gg 40$, so that the electron cyclotron energy is much larger than 1 keV, and we consider only states where all electrons are in the Landau ground state. The radius in the plane perpendicular to the field for the free electron wavefunction is $b^{-0.5} \ll 1$, expressed in atomic units. For the ground state of a neutral hydrogen atom, the transverse size of the electron distribution is again $b^{-0.5}$. The size parallel to the field is less than an atomic unit by only a moderate factor of order $\ln b$. The electron density is thus about $b(\ln b)$ and the ground-state binding energy (ionization potential) Q_1 is of order 0.2 $(\ln b)^2$, both in atomic units [3, 4]. For excited states with azimuthal quantum numbers $m = 1, 2, 3, \ldots$, the transverse size is larger than for $m = 0$ by only a factor $(2m + 1)^{0.5}$. The electron distribution is still elongated parallel to the field direction as long as $(2m + 1) \ll b^{0.5}$. One can then form a polyatomic H_n molecule by covalent bonding of these elongated atoms with $m = 0, 1, 2, \ldots, n-1$. For the special case of $n = b^{0.2} \gg 1$ for a chain molecule, the spacing between protons and the transverse radius of the electron cylinder are both of order $b^{-0.4}$ and the binding energy per atom Q_n is of order $b^{0.4}$, all in atomic units. For $n \gg b^{0.2}$ saturation sets in, with the electron density of order $b^{1.2}$ and the binding energy per atom approaching Q_c, a constant of about $b^{0.4}$ atomic units.

The ratio of Q_c to Q_0, the ionization energy of a single hydrogen atom, is of order $(b^{0.2}/\ln b)^2$, which exceeds unity only when b exceeds about 10^5 and then increases as b increases [3]. The dissociation energy from $(n + 1)$ to n approaches Q_c only for n much larger than $b^{0.2}$.

3. The liquid phase and droplets

If two very long parallel chain molecules are placed side by side, with the protons staggered by half a unit, there is a Coulomb attraction. Many chain molecules, all parallel to the field, with spacings of order $b^{-0.4}$, have some of the features of a bound solid. The binding energy per proton of such a solid, relative to isolated chains, is rather small—of order $0.01Q_c$. The optimum lattice structure of the protons in a real solid in these strong fields is not yet known, but binding energy and density have been estimated fairly accurately. The neutron star atmospheric temperature is large enough for the condensed phase being liquid, but with similar energy and density.

The mass density of the condensed phase at zero or small pressure is about $(B \times 10^{-14}\ \mathrm{G})^{1.2} \times 1.4 \times 10^5$ g cm^{-3} and the binding energy Q_s per proton, relative to free protons and electrons is about $(0.6b^{0.4})$ a.u. The value of this binding energy is known to within a small percentage at the moment and the cohesive energy $(Q_s - Q_1)$ relative to neutral hydrogen atoms exceeds $0.2Q_1$ if B exceeds 10^{14} G. We shall now only consider really strong fields, where the stability of the liquid phase in bulk is quite clear, but the value of the surface energy of a small liquid droplet is uncertain. This uncertainty is due to the fact that the cohesion energy per atom, of the condensed phase relative to separate isolated chain molecules, is $(Q_s - Q_c)$ which is quite small and therefore uncertain: the fraction $\Delta = (Q_s - Q_c)/Q_s$ is only about $(0.005–0.05)Q_s$.

We can nevertheless make some crude estimates of the shape of a small droplet and of its surface energy, which would be needed for nucleation theory if the condensation of a supersaturated vapour is to be followed in time. Consider a droplet, containing N hydrogen atoms, in the form of (pt^2) parallel chain molecules of length n units each, so that $N = (pt^2 n)$. For a large enough droplet, so that $n \gg b^{0.2}$, saturation has set in and the surface energy at the ends of the chains is of order $(2pt^2)Q_s$. The surface energy at the circumference of the droplet cylinder is of order $\Delta(2ptn)Q_s$ and the optimized shape of the droplet is elongated with t/n of order $\Delta \ll 1$. The total surface energy is of order $\Delta^{1.33}N^{0.67}Q_s$, for $N \gg b^{0.6}$. For $N < b^{0.2}$, on the other hand, one has a single chain molecule where saturation has not yet set in, so that the surface energy is of order NQ_s.

The critical temperature, below which the liquid phase and a saturated vapour can co-exist, has not yet been calculated as a function of field strength but crude estimates have been made [3]. For the 'middle of the range' field strength of order 10^{13} G the critical temperature is rather uncertain, but is probably below 10^5 K. Neutron star photosphere temperatures are larger than that, so there is no condensed hydrogen, but H, H_2, H_3 and other polyatomic molecules may be of interest. We consider now only the stronger fields, where the critical temperature is larger and better known, for example, about $10^{5.6}$ K and $10^{6.3}$ K, respectively, for 10^{14} G and 10^{15} G.

4. The neutron star atmosphere and pycnonuclear reactions

Model calculations for static neutron star atmospheres have been carried out for various field strengths and photospheric temperatures, but only for conditions where no liquid phase is present [5, 6]. For photospheric temperatures of order 10^6 K, the pressure scale height is a few centimetres and the photospheric density is about (0.1–1) g cm^{-3}. Above the photosphere the density decreases at almost constant temperature; below the photosphere the density and temperature both increase, roughly adiabatically. For very strong fields we now consider that the photospheric temperature can be less than the critical temperature, in some cases by a considerable factor. Consider now a case where this factor is sufficiently large, so that the saturation vapour density of the vapour in equilibrium with the liquid at the photospheric temperature is less than the liquid density by a factor of more than 10^5. This density is then less than the photospheric density would be in a purely gaseous atmosphere, so there is a layer *above* the photosphere at this density with vapour above and liquid below. This layer can be thought of as an 'ocean surface', which is observable since the vapour above is optically thin. At least for a static atmosphere, there is pressure equilibrium and continuity in temperature but a large jump in density at this ocean surface layer. The pressure increases as one goes deeper, at first with a slow increase in density, and both density and temperature eventually increase above critical values.

For fields of about 10^{14} G, the vapour immediately above the ocean surface is a mixture of various species: ionized hydrogen, neutral hydrogen atoms and a few polyatomic molecules. For fields of 10^{15} G and larger the situation is simpler: the vapour everywhere above the ocean surface is mostly ionized, simply free protons and electrons. We do not consider a static atmosphere but slow accretion, so the inflowing matter must change from vapour to liquid during the flow. If the surface energy of small droplets had been very small, a very small degree of supersaturation would have been sufficient for homogeneous nucleation to achieve the conversion from vapour to bulk liquid. However, we saw in section 3 that the surface energy of small nucleation droplets is actually quite substantial, homogeneous nucleation would be quite slow and one should worry about how raindrops actually form in the descending vapour, how the latent heat is disposed of, whether there are surface waves, etc. None of this has been studied yet, but there is an additional complication—pycnonuclear reactions.

The hydrogen flowing onto a neutron star surface is finally burned into helium, initiated mostly by the p–p reaction [1]. If the hydrogen were in the form of a neutral hydrogen gas in a strong magnetic field, the rate is enhanced slightly by electron screening [7]. However, reaction rates are enhanced enormously if the matter density is very high, even if the temperature is low [8, 9]. Usually, these high densities are achieved through very high pressures, but liquid hydrogen has a very large density in strong magnetic fields, even if both the temperature and the pressure are quite low. The inflowing hydrogen can burn, almost as soon as it has condensed into the liquid phase—'the real zero-pressure cold fusion'! It is not clear yet whether this burning proceeds smoothly or whether there is relaxation oscillation or other instability. 'Anti-thermal explosions' are a possibility, where cooling leads to condensation, leading to hydrogen burning and heat release, followed by evaporation which stops the burning and the heat release, leading to further cooling of the vapour, etc.

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