PLASMA PHYSICS

Plasmas everywhere

Richard D. Petrasso

ALTHOUGH described as the fourth state of matter, plasmas — gases of ionized atoms and molecules — are in fact the rule, not the exception, in the Universe. It is the clement conditions of Earth that make them seem a rarity. Exciting advances in space plasmas and in controlling laboratory plasmas, be they for controlled nuclear fusion or for X-ray lasers, were a feature of a recent wide-ranging meeting*.

Of the visible matter in the Universe, over 99 per cent consists of plasmas. Taking the case of the Solar System, the mass is totally dominated by a gravitationally confined sphere of plasma — the Sun. Although often considered to be electrically neutral mixtures of (ponderous) ions and (highly mobile) electrons, plasmas can also comprise a single charged species, such as trapped electrons, ions, positrons or antiprotons. Because plasmas, whether neutral or not, consist of such charged particles, they can support and react to electric and magnetic fields and exhibit a wide variety of collective modes, waves and instabilities. In fact these collective properties are exploited in beams of charged particles in particle accelerators and coherent radiation devices such as free electron lasers and gyrotrons.

Mirroring this diversity in character is the exceptional range of scales of plasmas (Fig. 1), from 10^{-3} to 10^{9} K in temperature and from 10^{2} m^{-3} to 10^{32} m^{-3} in density. At the high-density end of the spectrum, laboratory carbon/deuterium plasmas compressed by laser pressure (S. Nakai, Osaka Univ.) recently achieved a record density (around 600 g cm^{-3}). For the deuterium component, this is only a factor of three less than the proton number density (10^{32} m^{-3}) in the solar core. At the opposite end of the density spectrum, the Voyager spacecraft observed tenuous (10^{2}–10^{3} m^{-3}) high-energy protons in the magnetospheres of Saturn and Neptune (S. M. Krimigis, Johns Hopkins Univ.). For both planets, despite their intrinsic differences, the magnetospheric bulk proton temperature is 640×10^{6} K (Fig. 2). Even at this elevated temperature, there exists a population of protons in the high-energy tail whose effective temperature significantly exceeds the bulk value. The fascinating challenge presented by these observations is to identify a heating or acceleration mechanism by which magnetospheric protons can reach such elevated temperatures and energies. Not only must a satisfactory theory account for this heating, but it cannot depend sensitively upon the angle between the planetary rotation and magnetic axis (about 1° for Saturn, and an unexpected 47° for Neptune). An equally fundamental problem is the origin of the magnetic dynamo that generates not only the solar but planetary magnetic fields — and hence the magnetospheres — for Saturn, Neptune, Uranus, Jupiter and Earth (see the News and Views article by H.K. Moffatt, *Nature* **341**, 285–286; 1989).

The most celebrated application of magnetically confined neutral plasmas is the attempt to generate controlled nuclear fusion through so-called 'tokamaks', toroidal plasma-containment devices in which a large magnetic field (2–12 tesla) and plasma current (50 kiloamps to 6 megamps) thread the torus thereby inhibiting the loss of hot plasma particles. One of the notable results was the near achievement at the Joint European Torus of plasma conditions required for equivalent fusion breakeven (M. Keilhacker, JET, Oxford). Breakeven is a conceptual landmark for fusion physics wherein the power from fusion reactions, usually assumed to arise in a fuel mixture of deuterium (D) and tritium (T), equals the input power needed to heat the plasma.

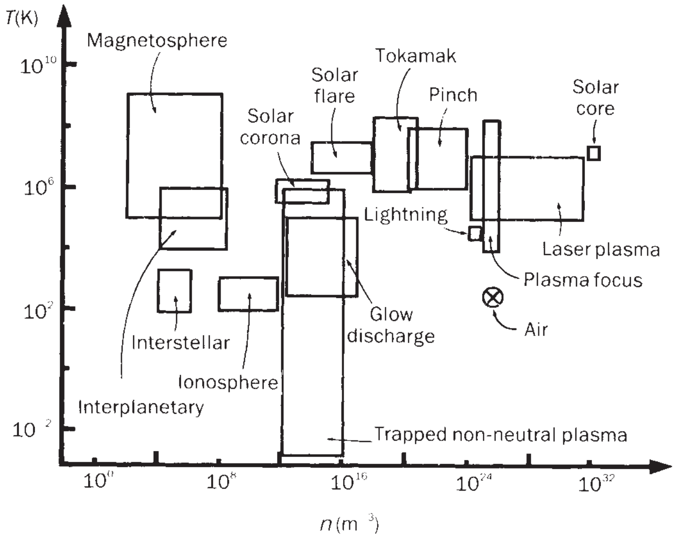

FIG. 1 A qualitative density–temperature map of plasmas. In density n the range spans 30 orders of magnitude, in temperature T, 12 orders. For reference, the ⊗ marks the density and temperature of air.

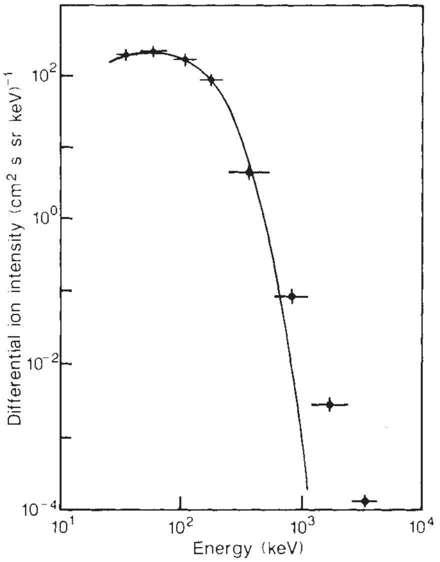

FIG. 2 Proton energy distribution for the magnetosphere of Saturn. The maxwellian curve (solid line) is a fit to $T = 640 \times 10^{6}$ K (55 keV). Even for this remarkably high temperature, significant deviations still occur for proton energies above 600 keV. What mechanism generates this elevated temperature and high-energy, non-maxwellian component? The proton energy distribution for Neptune's magnetosphere is strikingly similar to that of Saturn. (Courtesy of S. Krimigis, Johns Hopkins Univ.)

The figure-of-merit that measures the approach to breakeven, and also to the more meaningful goal of plasma ignition, is the triple product, $Tn\tau$, where T is the central ion temperature, n the central ion plasma density, and τ the global energy confinement time (the duration for which the plasma heat can be effectively trapped). Near the temperature peak in a deuterium discharge (Fig. 3), JET reached a record $Tn\tau$ of 1×10^{28} K m^{-3} s for 0.1 s (T=250×10^{6} K, $n = 3.7 \times 10^{19}$ m^{-3} and $\tau \approx 1.1$ s). With a plasma fuelled by a deuterium–tritium mixture in a discharge similar to this one, JET would have momentarily obtained 80 per cent of breakeven. This would correspond to 13 MW of fusion power being generated at the peak temperature by the reaction $D + T \rightarrow n\ (14.1\ \text{MeV}) + {}^{4}He\ (3.5\ \text{MeV})$. For plasma ignition, a further improvement by a factor of 6 is needed for $Tn\tau$. Contrast this, however, with the 25-order-of-magnitude excess over the threshold value for D–T ignition found in the Sun ($T = 15 \times 10^{6}$ K, $n = 1 \times 10^{32}$ m^{-3} and $\tau = 3 \times 10^{14}$ s).

JET's recent success largely stems from inhibiting carbon, oxygen, nickel and other contaminants from entering the plasma either at contact points between the plasma edge and internal tokamak

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*American Physical Society, Division of Plasma Physics, annual meeting, Los Angeles, 13–17 November 1989.

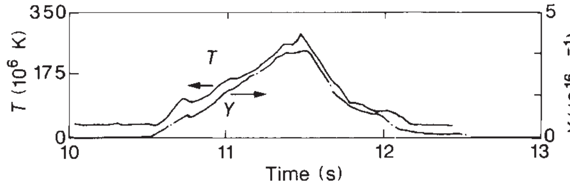

FIG. 3 Time evolution of central ion temperature (left axis, T) and D–D neutron rate (right axis, Y) for JET plasma discharge 20981 (D–D → n+^{3}He). At 11.4 s the temperature peaks at 250 × 10^6 K, which is 17 times hotter than the Sun's core (15 × 10^6 K). Most importantly, the $Tn\tau$ product (see text) also peaks at this time. At 11.5 s, the temperature and $Tn\tau$ drop precipitously owing to an influx of carbon impurities. The principal aim for JET now is to eliminate such influxes. (Courtesy of M. Keilhacker.)

structures or from sputtering (ion–surface collision) processes. When too many impurities inadvertently enter the plasma, n and T dramatically decrease owing to fuel dilution and increased radiative losses. JET reduced the impurity levels by replacing carbon tiles in the tokamak with beryllium ones and coating the remaining interior surfaces with beryllium. In fact the sharp reduction in peak temperature (250 × 10^6 K) at 11.5 s (Fig. 3) is a direct result of the rapid influx of carbon from graphite tiles yet to be replaced.

In the domain of laser/plasma physics, two novel developments were, first, the initial demonstration of an X-ray laser operating at 44.83 Å (B. J. MacGowan, Lawrence Livermore National Lab.), which is just to the long wavelength side of the carbon K-shell X-ray absorption edge; and, second, the application of table-top high-power lasers (H. Milchberg, Univ. Maryland) to the generation of plasmas with densities equalling those of solids (10^{29} m^{-3}). The X-ray laser work uses two arms of the Nova laser at Lawrence Livermore to ionize a thin strip of tantalum (73 electrons) down to the closed-shell, nickel-like state (28 electrons). Many of these nickel-like ions are collisionally excited from the $3d$ to the $4d$ shell. The lasing action, about 400 ps in duration, occurs between $4d$ and $4p$ states. There is interest in this particular wavelength because such radiation could be applied to the holography of (carbon-rich) biological specimens. At wavelengths slightly longer than the carbon K-shell edge (43.7 Å) there is sufficient scattering in the specimen to achieve good contrast while still minimizing the adverse effects of specimen heating through absorption (R. A. London, M. D. Rosen & J. Trebes *Appl. Optics* **28**, 3397–3404; 1989). Experiments in the near future will concentrate on doubling the X-ray path length in the Ta plasma (currently sufficient to give laser amplification by e^4) by the addition of a normal-incidence X-ray mirror at one end of the lasing medium.

The application of short-pulse (subpicosecond), table-top, millijoule lasers to irradiate solid targets is also an active area of research. This is partly a result of being able to generate warm plasmas (10^4–10^6 K) at solid-like densities. When these lasers operate with a very small prepulse, the density scale length at the laser–plasma interface can be of the order of or less than the collisionless skin depth, $c/\omega_p \approx 200$ Å (c is the speed of light, ω_p the plasma frequency). An intriguing feature of such plasmas is that they can probe regimes for which the plasma coupling parameter (Γ), the ratio of interparticle potential to kinetic energy, is of the order of 1 (for example, at $T \approx 10^5$ K and $n \approx 10^{29}$ m^{-3}). Much of classical (not quantum degenerate) plasma physics concerns weakly coupled regimes for which $\Gamma << 1$. This is the case for (Voyager) space plasmas ($\Gamma \sim 10^{-13}$), tokamak plasmas ($\Gamma \sim 10^{-6}$), the X-ray laser plasmas ($\Gamma \sim 10^{-3}$) and even the solar core ($\Gamma \approx 0.1$). At the other extreme, recently achieved non-neutral trapped-ion plasmas have yielded $\Gamma \geqslant 10^2$ and are therefore strongly coupled. Thus plasmas with $\Gamma \sim 1$, such as those made by short-pulse lasers, form a pivotal bridge linking weakly and strongly coupled plasmas. ☐

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CONSERVATION

What the little birds tell us

Jeremy J. D. Greenwood

THE consequences of the destruction of tropical forests are not always immediately apparent to citizens of the developed temperate zone. But now, in identifying a general decline in populations of birds that breed in eastern North America and winter in the neotropics, Robbins and colleagues[1] report strong evidence that deforestation in the tropics has a direct effect on the natural history of a temperate region. Two-thirds of the pairs of breeding birds in many North American forests are neotropical migrants[2] and American birdwatchers have been asking "Where have all the birds gone?". Once again, as in the controversy over pesticides in the 1950s and 1960s, birds are proving useful indicators of the widespread ecological effects of human activities. There has, however, been disagreement about the extent of the population declines and whether their causes are to be found on the summering or the wintering grounds.

IMAGE
UNAVAILABLE
FOR COPYRIGHT
REASONS

Kevin Baker

Bay-breasted warbler, *Dendroica castanea*, a typical long-distance migrant that breeds in northern forests and winters in the neotropics. Its breeding numbers declined by almost 16 per cent each year between 1978 and 1987.

We know a great deal about bird populations because thousands of volunteers are prepared to collaborate in survey work, such as the North American Breeding Bird Survey (BBS)[3]. During the first 15 years of the survey (1965–79), no general decline in the populations of neotropical migrants was apparent, so Hutto[4] has argued that reports of such declines result from local changes in the breeding areas — fragmentation of American and Canadian forests, for example. He has pointed out that many of the migrants are common in disturbed, non-forest habitats in winter, and so are unlikely to have been adversely affected by the destruction of neotropical forests.

Many studies do indeed show that forest fragmentation in the North American breeding grounds particularly affects long-distance migrants and species living in the interiors of forests: their population densities are lower in small areas of woodland than in large areas, and at least some of the local declines have occurred only in such small fragments[5]. Why should long-distance migrants be particularly sensitive to forest fragmentation? Two clues are that a decline in a small woodlot which coincided with removal of local forests was reversed when the forests became re-established[6], and that long-distance migrants have higher rates of return to breeding sites in subsequent years than do residents and short-distance migrants[5]. The second observation may simply reflect the generally higher survival rates of migrants than of residents; but perhaps the long-distance migrants, which do not return to their breeding area until shortly before nesting