PLASMA ASTROPHYSICS

How to see a black hole

One way to collect data about black holes is to analyse the X-rays emitted from the surrounding plasmas heated to extreme temperatures by the flux of photons flowing into them. The use of intense lasers to recreate these conditions in the lab provides a potentially valuable tool for understanding what these data mean.

R. Paul Drake

As matter falls onto a massive compact astrophysical object, such as a black hole or a neutron star, gravitational energy is converted into kinetic energy and heat. The resulting disk of accreting material (or 'accretion disk') becomes hot and glows brightly. Ironically, this makes black holes glow (Fig. 1). By analysing the radiation emitted from the glowing region around a black hole, one can attempt to study how black holes behave and thereby test our fundamental assumptions about the Universe[1]. Unfortunately, being relatively few in number (compared to the number of more ordinary astrophysical objects in the Universe) and a great distance away, interpreting the radiation we receive from them is challenging.

On page 821 of this issue[2], Fujioka and colleagues report the use of high-intensity lasers to try to recreate conditions similar to those in the vicinity of a black hole, enabling processes occurring in these and other massive compact astrophysical objects to be studied in the laboratory. They compare their data with X-ray spectra obtained from Cygnus X-3, which is a binary system consisting of a black-hole candidate and a companion star, and Vela X-1, also a binary system that comprises a neutron star and a supergiant. In their investigation they uncover potential errors in previous interpretations of astrophysical data, caused by an apparent misidentification of the origin of one of the lines in the spectra. If Fujioka *et al.* are correct, this might alter conclusions about the structure of the environment surrounding these compact objects. More importantly, their experiments demonstrate an innovative and flexible approach to the study of this type of glowing system, with many related potential applications.

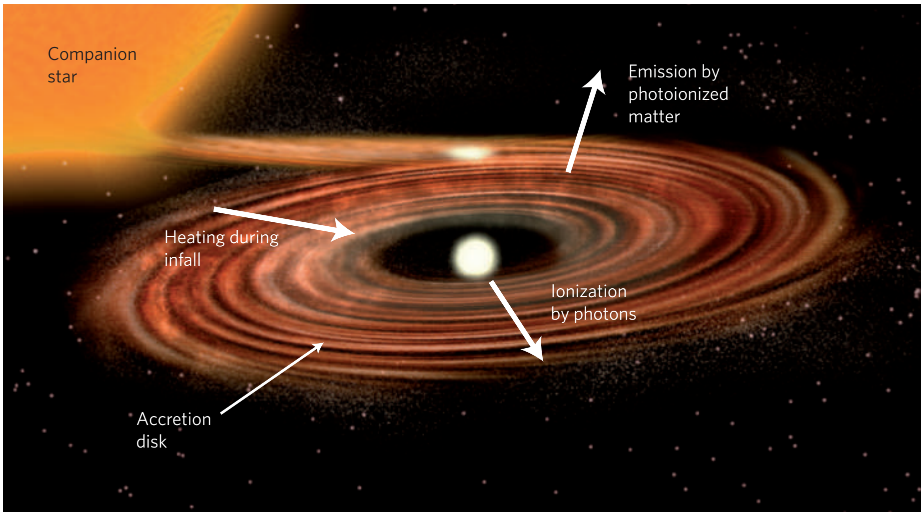

Figure 1 | The vicinity of a black hole and companion star. Matter flows from the companion into the accretion disk around the black hole and then is heated as it falls inwards. The emission from the hottest, innermost material photoionizes the material in the accretion disk. We can observe the emission from this photoionized matter. (Adapted from an image courtesy of P. Marenfeld and NOAO/AURA/NSF.)

Nearly all plasmas, whether in Earth-bound laboratories, stars and their environs, or interstellar space, are collisionally ionized. This means that the degree of ionization is determined primarily by the collisions of ions and electrons. The result is that the material is ionized into a state in which the ionization energy is only a few times the temperature of the plasma. To achieve single ionization of the atoms in a silicon plasma requires 8 eV of energy per atom (equivalent to a temperature of about 100,000 K), and to achieve complete ionization so that its atoms are stripped of all 14 of their electrons requires more than 2,000 eV per atom (about 20,000,000 K).

In contrast, much of the plasma environment around a massive compact astrophysical object is photoionized. Photoionization becomes dominant when a very hot source irradiates a cooler region, and allows a plasma to be excited to a much higher ionization state than its temperature would otherwise dictate. The physical processes that govern the radiation emitted from photoionized plasmas are different to those governing ordinary ones. Consequently, to accurately interpret the spectra emitted by compact objects requires understanding beyond conventional plasma physics. This includes more sophisticated understanding of photoionization cross-sections (related to ionization probability) and also the interaction of photoionization with collisional ionization, photon emission, and recombination of ions with electrons. For any real plasma, one must also understand the spatial structure and any interactions between emissions from one region with absorption processes in another.

In seeking to understand their data, Fujioka *et al.* invoke a more sophisticated model of atomic structure than has been conventionally used to identify the origin of astrophysical X-ray lines. This is one of the advantages of laboratory experiments — that is, they allow researchers to account for in more detail all the competing processes that produce the resulting X-ray emission, which typically contains fewer lines to be identified. The resulting detailed focus on the structure of specific atoms always has the potential to lead to new discoveries, and this study seems to have done so.

The potential to generate and study photoionized plasmas of astrophysical relevance in laboratory experiments is largely under-appreciated, even in the present work. I believe the reason for this has to do with the way in which astrophysicists traditionally characterize them — that is, in terms of the environmental parameter, ξ, which has units of energy multiplied by distance per unit time. This parameter is defined as $\xi = L_x n_e / r^2$, where L_x is the luminosity of the source creating the photoionization (in units of energy per unit time), n_e is the electron density at the observed location, and r is the distance from the source to the observed location. Most of the literature on photoionized astrophysical plasmas report ξ ranging from 10 to 10^4 erg cm s^{-1}. However, these limits are not fundamental. The lower-bound value is determined by the satellite-based instruments used to collect X-ray spectra, and the upper-bound value is set by the amount of energy it takes to fully ionize a plasma that contains the elements typically found in most astrophysical objects. Consequently, it is very likely that strongly photoionized plasmas could lie outside this range. Moreover, the use of any dimensional parameter (such as ξ) to characterize a physical regime is inherently problematic. In my view, it is much better to use a dimensionless (and therefore scale-invariant) parameter that captures the detailed atomic physics occurring in the system, rather than ξ, which from a physics point of view is rather arbitrary. In the present case, a much better parameter[4] is the ratio $\xi\phi/C$, where ϕ is the photoionization cross-section per photon energy and C is the rate coefficient for collisional ionization (having units of volume per unit time). For the experimental conditions of Fujioka *et al.*, $C < 10^{-10}$ cm^3 s^{-1} for the ionization of Si^{11+} at an electron temperature equivalent to 30 eV, and $\phi \sim 10^{-8}$ cm^2 erg^{-1} for photoionization at kiloelectronvolt energy by a 500 eV source. Thus, with ξ taking units of erg cm s^{-1}, one has $\xi\phi/C > 100\xi$, implying that any plasma having $\xi > 0.1$ is very dominantly photoionized. This includes the case of the present paper, in which the value of ξ is measured to be ~6, otherwise considered outside the conventional range.

The approach of Fujioka *et al.* has great potential for further development. Previous laboratory studies have used X-ray sources having energies near 100 eV, produced either from current-driven implosions of metallic plasmas[5,6] or from laser irradiation of high-atomic-number materials[7]. The new technique enables the energy of the photon source to be varied from <100 eV to at least a few kiloelectronvolts, and also enables more and greater control over the structure and composition of the photoionized material. To reach their potential, such experiments will need more complete diagnostics of the plasma structure.

The study of photoionized plasmas is just one example of the sorts of experiment that can be carried out in the emerging field of high-energy-density laboratory astrophysics (HEDLA). HEDLA is the area of plasma astrophysics[4] that studies plasmas[8] having pressures of the order of a million atmospheres or more. Another area where HEDLA has had a direct impact is in the destruction of clumps by shock waves, in which laboratory data[9] was used to directly interpret[10] the morphological stage of one such interaction. Beyond its contribution to understanding black holes (strong gravity) discussed above, HEDLA research has the potential to contribute to our understanding of the nature of dark energy, the operation of cosmic accelerators, the origin of the heavy elements, and exotic states of matter. □

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HIGH-TEMPERATURE SUPERCONDUCTIVITY

Alive and kicking

The discovery of iron-based pnictide superconductors may have reinvigorated the field of high-temperature superconductivity, but the cuprate superconductors are still in the game.

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In 2006, high-temperature superconductivity (HTS) was forecast to become prematurely extinct sometime between 2010 and 2015, following the so-called scientometric analysis of the publication statistics during its short lifetime of 20 years[1]. Instead, recent discoveries in the field promise more exciting opportunities for unravelling the mystery of HTS and to raise the transition temperature T_c to new heights in the years to come.

In the Bardeen–Cooper–Schrieffer (BCS) framework, the conventional electron–phonon interaction for electron pairing has been shown to allow a maximum T_c of roughly only 30 K without triggering a lattice instability catastrophe. The highest recorded T_c in high-temperature superconductors is 134–164 K. We are thus confronted with the question: "What is the mechanism that can lead to such a high T_c?" Furthermore, many properties of HTSs defy the predictions of the Fermi-liquid theory, on which the BCS model is based. This raises another question: "Is a new paradigm needed for HTS?" The 9th International Conference on Materials and Mechanisms of Superconductivity (M^{2}S-IX) was held between 7–12 September 2009, in Tokyo, Japan, to address these questions. The challenges and potential benefits of HTSs for applications were also briefly reviewed and discussed.

Reports at M^{2}S-IX covered all known superconducting materials systems. The iron pnictide system was the favourite topic of conversation, displacing the cuprates as the most-discussed materials for the first time at any HTS conference since 1987. In early 2008, Hosono *et al.*[2] found LaFeAsO to be superconducting with a T_c up to 26 K when doped with fluorine. Being a non-cuprate with a relatively high T_c in the presence of a high magnetic iron content, it has generated great interest worldwide, raising hopes of setting a new T_c record and of explaining the role of magnetism in HTSs. Six homologous series of iron pnictides and iron chalcognides were subsequently discovered. Each has the distinct layered structure with active Fe_2As_2 layers, in which superconductivity occurs, separated by perovskite-like blocking layers, in which modulation doping into the Fe_2As_2 layers takes place. Their structures