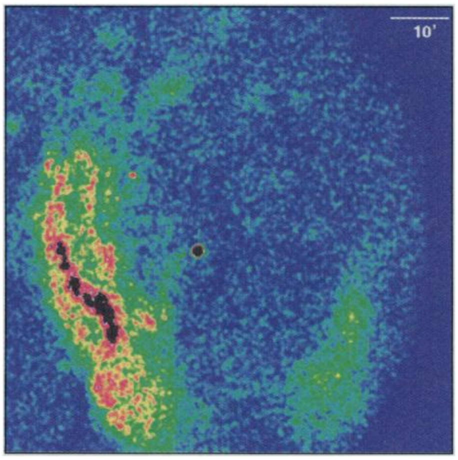
Isolated Neutron Stars

Giovanni F. Bignami

Isolated neutron stars (INSs) in our galaxy are believed to be active for a relatively small fraction of their lifetime of $\sim 10^{10}$ years. After their violent but extremely short nonthermal phase, they are visible as radio pulsars for $\sim 10^{6.5}$ years. According to most scenarios for how they cool after being born in a supernova, neutron stars maintain a surface temperature of more than $\sim 10^5$ K for the same time period. Thus, about 10^{-3} of the INS population might be detected either as radio pulsars or through their thermal surface emission, assuming they are sufficiently hot and luminous to be picked up by the current generation of x-ray, ultraviolet (UV), and optical telescopes, which only sample a very small volume of our galaxy. When the radio mechanism fades away and their surface temperature drops, the INSs become invisible and just sit there, making up a fraction of the galactic dark baryonic matter. They can be revived by a companion (either coeval or met later) from which they start accreting matter, are spun up, and become "millisecond pulsars." These can no longer be considered isolated, that is, self-powered by either rotation or latent heat.

In principle, old INSs could also be revived by accretion from the interstellar (IS) medium (*1*). This mechanism, however, is intrinsically difficult for several reasons. The accretion rate is inversely proportional to the cube of the object's velocity, and INSs are the fastest stars in our galaxy (*2*). It is proportional to the density of the ambient medium, and old INSs, born in the disk, have had ample time to move away from the densest regions of the galaxy. Moreover, if one individual object were to slowly plunge into a dense interstellar cloud, and thus significantly accrete, there would be little evidence of its presence, owing to the great capacity of IS clouds to absorb hot thermal radiation. It is thus no surprise that, so far, in spite of their computed high spatial density (several hundreds in a sphere of 100 pc around the sun), no firm evidence for detection of such old (>>10^5 years) INSs has been found.

However, in very recent years, better luck has been enjoyed by researchers looking for somewhat younger INSs, those stars that are still thermally active. About 20 objects are now visible at wavelengths other than radio (*3*) (where 700 pulsars are known), using the combined power of the ROSAT (x-ray), the EGRET (gamma ray), the EUVE (extreme UV), the HST (optical and UV) space telescopes. This database is important for addressing emission mechanisms in INSs (*4*).



Pinpointing a young neutron star. ROSAT PSPC image of 1E 1207-5209 (obtained using archived data) shows a strong pointlike source, most probably an INS, inside the SNR G296.5 + 10.

Of truly special interest are about seven of the objects, reported somewhat en passant very recently, for which the evidence for INS nature is strong but which are not seen as radio pulsars. For all of them, the high value of the x-ray to optical flux ratio, F_x/F_{opt}, coupled with a good (~1 arc sec) position but with no radio source in it, points to a radio-quiet INS. Another clue is their spectral shape, well described by a thermal law at the expected temperatures. The lack of strong pulsation in x-rays is not a problem: no a priori knowledge of the period, limited statistics, and intrinsically shallow modulation renders such a search very difficult. Four of the candidates (*5–8*) appear related to relatively young supernova remnants (SNRs). Among these is 1E 1207-5209, the first radio-quiet INS to appear after Geminga (see figure). If true, this correlation with SNRs also gives an age to these objects: by NS standards, they are all very young. In fact, the absence of the strong, flat-spectrum nonthermal emission is mildly surprising, especially for 1E 0820-4247 (*5*), which is inside the Puppis A SNR and supposedly only 3700 years old. Could this be related to the absence of radio emission? Could this imply that all nonthermal processes are beamed away from the line of sight?

Be this as it may, these four objects are indeed very strong candidates for being neutron stars, emitting thermally and isotropically from most of their surfaces at a temperature compatible with their age. The remaining three are without an SNR. They include Geminga (*9*) and two recent candidates (*10, 11*). The first of these (*10*) has been reported to be possibly variable. This is not something an INS can easily do, whether it emits thermally or, even less likely, if it accretes from the ISM. The second object (*11*) is more convincing: it has no variability but has a high F_x/F_{opt}. However, the search for an optical counterpart remains incomplete, resembling the early stages of the Geminga search (*12*).

Why, then, are none of these seven objects, apart from Geminga, a gamma-ray source? It could be because of a distance-luminosity argument. A 10^5- to 10^6-year-old INS has a rotational energy output of less than $\sim 10^{34}$ ergs/s. Even if a big fraction (10 to 50%) of it goes into energetic photons, as is the case for PSR1055-52 (*13*), the sensitivity of the best gamma-ray telescope now available, EGRET on the Gamma Ray Observer (GRO), makes it difficult to detect such objects much beyond 1 to 2 kpc. However, there are more than 70 unidentified EGRET sources (*14*) awaiting the sort of detailed, painful study necessary to nail them. Some will turn out to be extragalactic, some will be different galactic objects, but quite a few could be INSs. The same could be true of the thousands of unidentified ROSAT x-ray sources.

We have learned by now that lack of coincidence with a known radio pulsar should not prevent a source from being considered an INS. With high-energy astrophysics, we have acquired a new tool for discovering these objects: they can be detected more easily in thermal x-rays and also in gamma rays, which are energetically very important. The score, 700 to 7, may still look very much in favor of radio astronomy, but who knows, many more could be there, already detected, only awaiting recognition.

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Intermittently Flowing Rivers of Magnetic Flux

Franco Nori

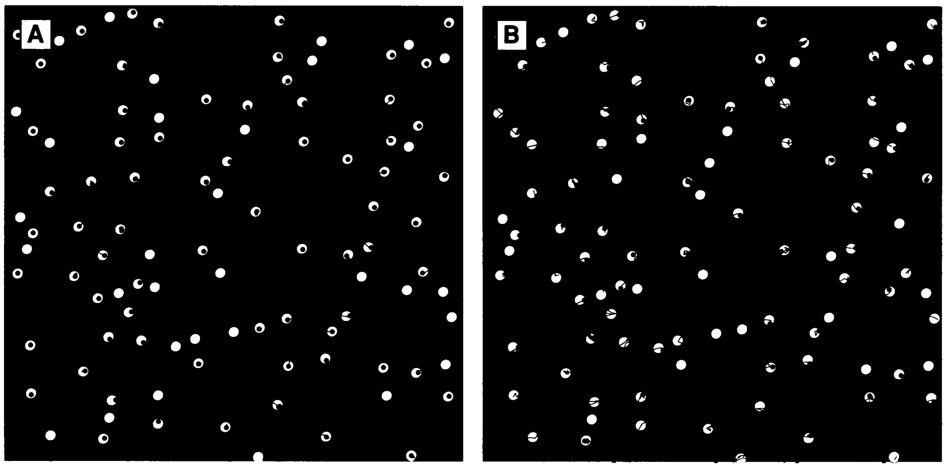
One of the major unsolved puzzles in superconductivity is the nature of the motion of penetrating flux lines. Magnetic flux enters a clean type II superconductor in the form of a regular triangular lattice of quantized magnetic flux lines (also known as vortices because electrical currents whirl around each flux line). When this lattice is forced to move, by application of either an electric current or a varying magnetic field, it maintains its regular periodic structure. The dynamics of this lattice of flux lines become more complicated when it is forced to move inside a disordered sample with pinning sites that can temporarily trap vortices. As the external magnetic field is increased, additional flux lines are forced inside the sample, where their motion is impeded by defects. When pinning is weak relative to the driving force, the array of flux lines flows smoothly, with some minor distortions, and behaves as an elastic medium (that is, like a flowing rubber sheet). If the pinning forces are very strong, the flux lattice remains immobilized. In the poorly understood intermediate regime, when pinning and driving forces are comparable, vortex motion is not expected to remain elastic, but to become plastic, where parts of the flux lattice break loose from the rest.

In this issue of *Science*, Tonomura and collaborators (*1*) present direct evidence of plastic flow of flux lines in a superconductor. Their experiments provide a striking motion picture of the onset of vortex motion that vividly illustrates the existence of flowing "rivers" of quantized magnetic flux that intermittently form, freeze, and reappear at different locations in the sample. These rivers flow around "islands" (or domains) of flux lines that are temporarily trapped by the pinning sites. The shape and size of these temporarily frozen islands abruptly change over time with every loading-unloading cycle. Movies of the phenomena [for figures 5 and 6 on page 1394 of (*1*)] are available from *Science*'s World Wide Web site at URL <http://www.aaas.org/science/beyond htm>.

Flux pinning in superconductors is of both technological and scientific interest (*2*). Practical applications of superconducting materials require that the magnetic flux lines be pinned, because the motion of flux lines dissipates energy and destroys the superconducting state. Therefore, it is important to understand how the trapping and depinning of flux lines occur. The complex nature of this onset of collective motion—with loading and unloading cycles, plastic flow, and intermittent avalanches—is not well understood, and it is the subject of intense investigations on both superconducting materials and a large variety of other systems: granular assemblies, magnetic bubble arrays, electron lattices in semiconductors, charge density waves, water droplets sprayed on a surface, and the stick-slip motion of two rubbing interfaces. These apparently dissimilar systems have interacting moveable objects (such as vortices, electrons, or grains) that repel each other and are pushed toward instability by an external driving force. During the unstable state, particle transport occurs in the form of avalanches or cascades that release accumulated strain in the system and allow the medium to move to a nearby metastable state. The detailed nature of the onset of collective transport in these systems is still hotly debated and continues to be an exciting area of research.

A remarkable feature of the technique used by Matsuda *et al.* (*1*) is the ability to monitor the spatiotemporal dynamics of the vortex lattice while simultaneously imaging the large pinning sites irradiated on the sample. This technique, called Lorentz microscopy, allows the microscopic motion of individual flux lines to be seen directly. Their observation of flux gradient–driven intermittent plastic flow is consistent with previous time-resolved experiments (*3*) and computer simulations (*4*) of vortices forced by an increasing magnetic field. Other studies of plastic flow [for example, (*5, 6*)] focused on the different case where the flux lattice is driven by an applied electrical current, whereas in (*1, 3, 4*), the varying external field provides the pressure that forces the vortices through the sample. Moreover, previous experiments on plastic flow were indirect, because they did not image the spatiotemporal evolution of the vortex lattice.

Several "magnetic snapshots" of the flux lattice are presented in (*1*). These directly show how the flux lattice orders when either the field or the temperature is increased. The main results of (*1*) are summarized in its figure 6, where successive video frames show a vortex lattice with several "frozen" domains (top frame), vortex streets



Branched vortex channels. Computer-simulated trajectories (black trails) of eastbound vortices (black dots) moving inside a superconductor with pinning sites (yellow circles). (**A**) Strong pinning produces a few vortex channels with heavy traffic, whereas (**B**) weak pinning induces a different network of much broader vortex trails. Indeed, in (*1*), the vortex channels also become wider at higher temperatures, when pinning is weaker. A short video clip of this figure is available at URL <http://science-mag.aaas.org/science/feature/beyond >.

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