ASTRONOMY

A Pulsar Bonanza

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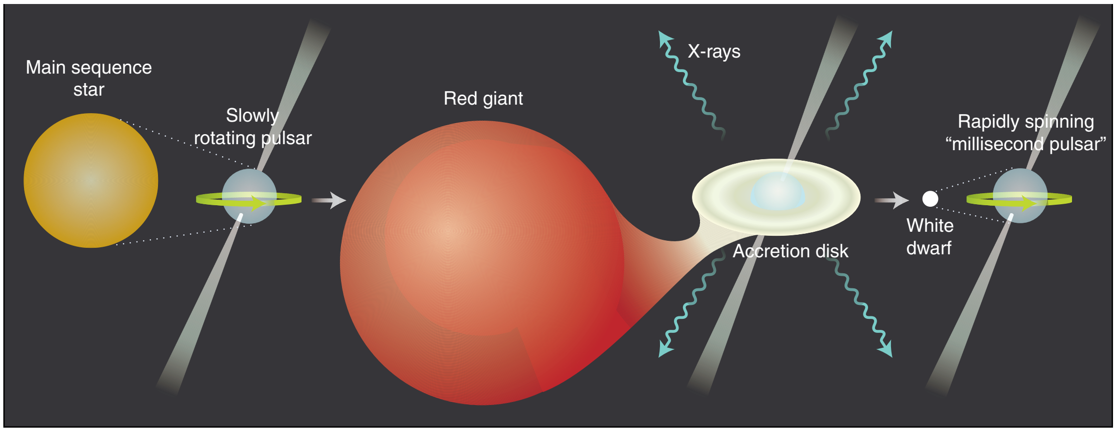
When a massive star explodes in a supernova, it leaves a compact object called a neutron star. The spin of the neutron star and its enormous magnetic field generate a rotating radiation beam. Rather like viewing a lighthouse from a distance, observers on Earth receive pulses of radiation each time the neutron star's beam crosses the line of sight of a radio telescope. The clocklike rotational stability of these objects—referred to as pulsars—has provided a wealth of insights into general relativity, galactic astronomy, planetary physics, and even cosmology.

Recent technological improvements and new instruments are enabling astronomers to find many new pulsars and to probe a rich variety of astrophysical settings. The latest breakthrough is the discovery of 21-millisecond pulsars in the globular cluster Terzan 5 by Ransom *et al.* [see page 892 of this issue (*1*)]. The study provides new opportunities for studying the extreme environments in globular clusters and the formation mechanisms for millisecond pulsars.

With rotation rates as fast as 642 Hz, millisecond pulsars act as cosmic flywheels that can sustain their rapid rotation on time scales of up to 10 billion years. In the most likely formation mechanism (see the first figure), a neutron star with a spin rate of a few hertz is spun up through the transfer of mass from a binary companion. The substantial heating of the material as it spirals into the strong gravitational field of the neutron star produces x-rays.

Such x-ray binaries exist in our own galaxy, but they are 10 times more common in globular clusters (dense conglomerations of 100,000 or more stars that are packed into a radius of about 10 light-years; they are about 200 times denser than the Milky Way). Globular clusters are excellent breeding grounds for millisecond pulsars, because the extremely high stellar density increases the probability of encounters between cluster members. For example, in a so-called exchange interaction (*2*), a neutron star or black hole can collide with a binary system and capture the more massive star to form a new binary.



Formation of a millisecond pulsar in a binary system. Initially, a slowly rotating pulsar orbits around a normal star (**left**). When the normal star reaches the end of its life and becomes a red giant, an x-ray binary is formed (**middle**). Material from the outer layers of the red giant is drawn toward the neutron star by its intense gravitational field, resulting in a disk of material that spirals into the neutron star. As a result of intense friction, the star is heated to more than 10^6 K and emits x-rays. The transfer of material onto the neutron star also transfers angular momentum from the orbit to the neutron star. This process can spin up the neutron star to rotation rates exceeding 500 Hz, consistent with the spin rates of the fastest rotating millisecond pulsars in Terzan 5. (**Right**) At the end of the red giant phase, the star sheds its outer layers and becomes a compact white dwarf that orbits around the rapidly rotating millisecond pulsar.

Before the new discoveries reported in (*1*), the record number of pulsars known in a single cluster was 22 in 47 Tucanae (*3*). Studies of the pulsars in 47 Tucanae, which have spin periods of 2 to 8 ms, have provided a wealth of information, including the first definite evidence for the existence of gas in a globular cluster (*4*).

As one of the densest and most massive clusters, Terzan 5 has long been thought to harbor many more pulsars than the three found in earlier searches (*5*–*7*). The main indication for this was the excess radio emission from the core of Terzan 5 (see the second figure). Assuming that the radio emission of the putative pulsar population is similar to that known from studies of other pulsars (*3*, *8*), this excess can be explained (*8*) by the combined emission of up to several hundred pulsars.

With the Green Bank Telescope, Ransom *et al.* (*1*) have carried out observations of Terzan 5 at 5 to 10 times higher sensitivity than previous searches (*5*–*7*) and have cracked the pulsar enigma in this cluster. With the 21 newly discovered pulsars, the total number of known pulsars in Terzan 5 is now 24. Individual pulsars are referred to by letters of the alphabet.

The spin periods and orbital parameters of the new pulsars are very different from those of the 47 Tucanae pulsars. The spin periods of the Terzan 5 pulsars span a much broader range (1.67 to 80 ms), including two rapidly spinning pulsars (O and P). Fourteen of the pulsars are binaries, including two systems with eccentric orbits (I and J). No such systems are known in 47 Tucanae. These contrasting pulsar populations may reflect the different evolutionary states and physical conditions of the two clusters. In particular, the central stellar density of Terzan 5 is about twice that of 47 Tucanae, resulting in many more stellar interactions that might disrupt the spin-up process in some binary systems and induce larger eccentricities in others.

Observations of the eccentric binaries I and J show that the point of closest approach of the two stars in each orbit changes with time. This relativistic effect is also seen in the orbit of Mercury, caused by the warping of spacetime close to the Sun. However, for I and J, the much stronger gravitational fields of the neutron stars mean that the rate of pre-

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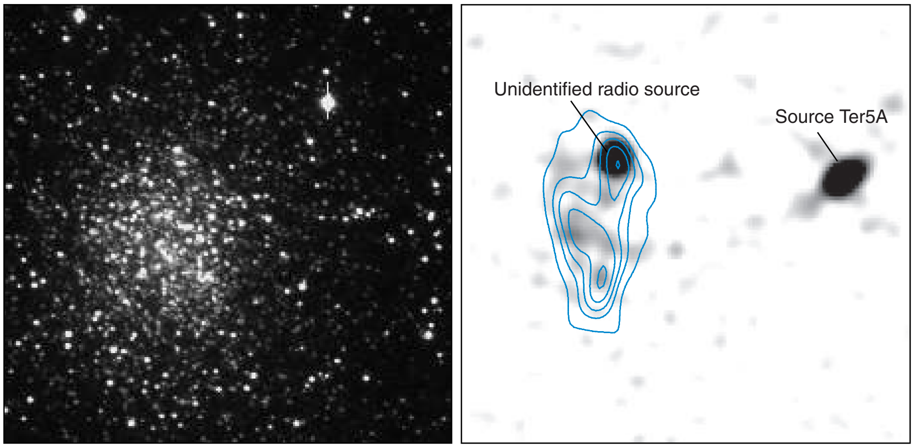

Are more pulsars lurking in Terzan 5? (Left) A false-color optical image showing a 1 by 1 light-year field of the central region of Terzan 5 taken with the European Southern Observatory's New Technology Telescope. (**Right**) Radio map of the same region. [Adapted from (*8*)] Radio source Ter5A is the first pulsar found in this cluster (*5*). Most of the newly discovered pulsars are likely to contribute to the central continuum emission. The "unidentified radio source" might be a bright millisecond pulsar in a compact orbit.

cession in these binary systems is about 0.3° per year, some 2600 times that of Mercury. Interpreting this precession with general relativity provides strong constraints on the masses of the two pulsars and their companions. Ransom *et al.* (*1*) demonstrate that the pulsar masses are likely to be at least 1.7 times that of the Sun, at the high end of the distribution of measured neutron star masses (*9*). This result indicates that these neutron stars accreted large fractions of a solar mass during their formation. It also provides strong evidence for the existence of massive neutron stars, which are not allowed by some models of matter at high densities (*10*).

Terzan 5 is now a hive of activity for observational and theoretical astronomers. Within a year, further Green Bank observations will provide precise locations and spin-down rates of the pulsars within the cluster. These observations will allow comparative studies at optical and x-ray wavelengths and will probe the mass (*11*) and gas (*4*) distributions in the cluster. The 24 pulsars found so far only account for half of the radio emission seen in the second figure, and more are likely to be discovered with current instrumentation. Of particular interest is the nature of the radio source north of the cluster center (see the "unidentified radio source" in the second figure). This enigmatic source may be a bright millisecond pulsar that has so far evaded detection by virtue of being in an extremely compact orbit, perhaps around a black hole. The identification of such a system is a key goal of pulsar astronomy, and Terzan 5 may be the place to find it.

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MATHEMATICS/COMPUTATION

Accelerating Networks

John S. Mattick and Michael J. Gagen

Networks that are simple connection networks, such as telephone exchanges or the Internet, are able to grow in an unconstrained way. In contrast, regulatory networks—such as those in biology (for example, the network of regulatory proteins that controls gene expression in bacteria), engineering, or society—are accelerating networks that must be able to operate in a globally responsive way. Such global responsiveness, we argue, imposes an upper size limit on the complexity of integrated systems due to the costs incurred by the need for an increased number of connections and levels of regulation.

Most network studies to date have focused on simple (and usually large) connectionist systems like telephone exchanges or the Internet. These networks are generally "scale-free," that is, they exhibit little change in their network structures or statistics as they grow, in terms of the average number and the distribution of their connections per node (*1*, *2*). These networks can become large precisely because they have no need to rapidly integrate information from or globally respond to the current state of their nodes. For example, it does not matter to the overall function of the Internet whether any particular individual is connected or not. The state of one node is quite irrelevant to most of the others, although the system as a whole is vulnerable to damage at nodes that have many connections (*3*).

The situation is different with functionally organized systems whose operation is reliant on the integrated activity of any or all of its component nodes. Good examples include stock exchanges, the *Science* editorial office, and the protein network controlling gene expression. In such circumstances, the number of informative connections per node must increase with the size of the network. This means that the total number of connections between nodes scales faster than linearly with node number (see the figure, top). Such networks are termed "accelerating" networks (*1*, *2*).

We contend that accelerating networks are far more common in the natural world than has hitherto been appreciated. These accelerating connection requirements, in principle and in practice, impose an upper limit on the functional complexity that integrated systems can attain. Maximal integrated connectivity occurs when all nodes are connected to all others (a proportional connectivity of 1), which means that the total number of connections in such networks scales quadratically with network size. Even if the proportional connectivity is much less than 1, the number of connections must still scale quadratically, otherwise global connectivity will decline. This in turn means that the size and complexity of such systems must sooner or later reach a limit where the number of possible connections becomes saturated or where the accelerating proportional cost of these connections becomes prohibitive.

This limit can be breached by a reduction in connectivity, which reduces the functional integration of the network, leading to fragmentation, as is observed, for example, in the

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