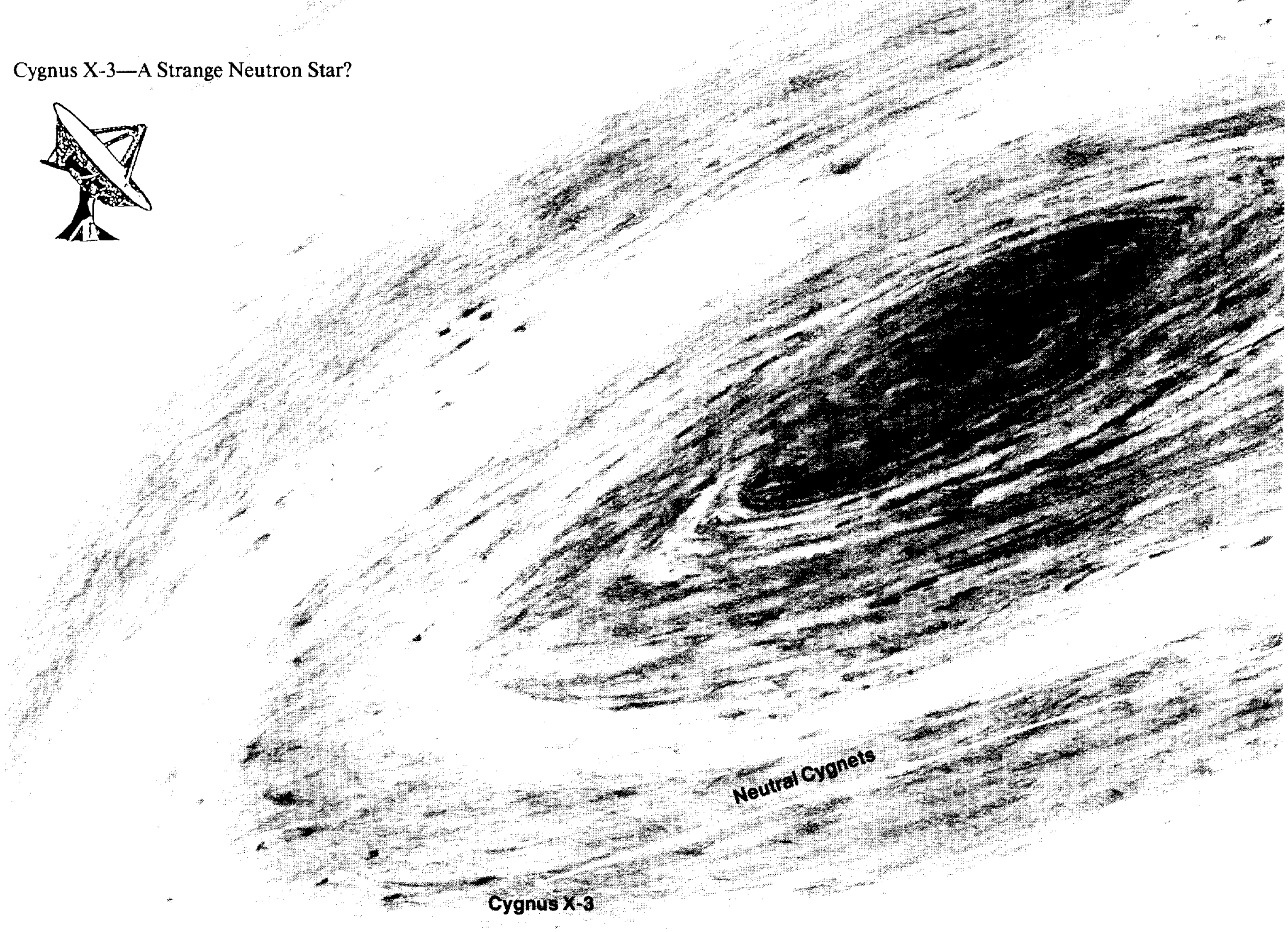
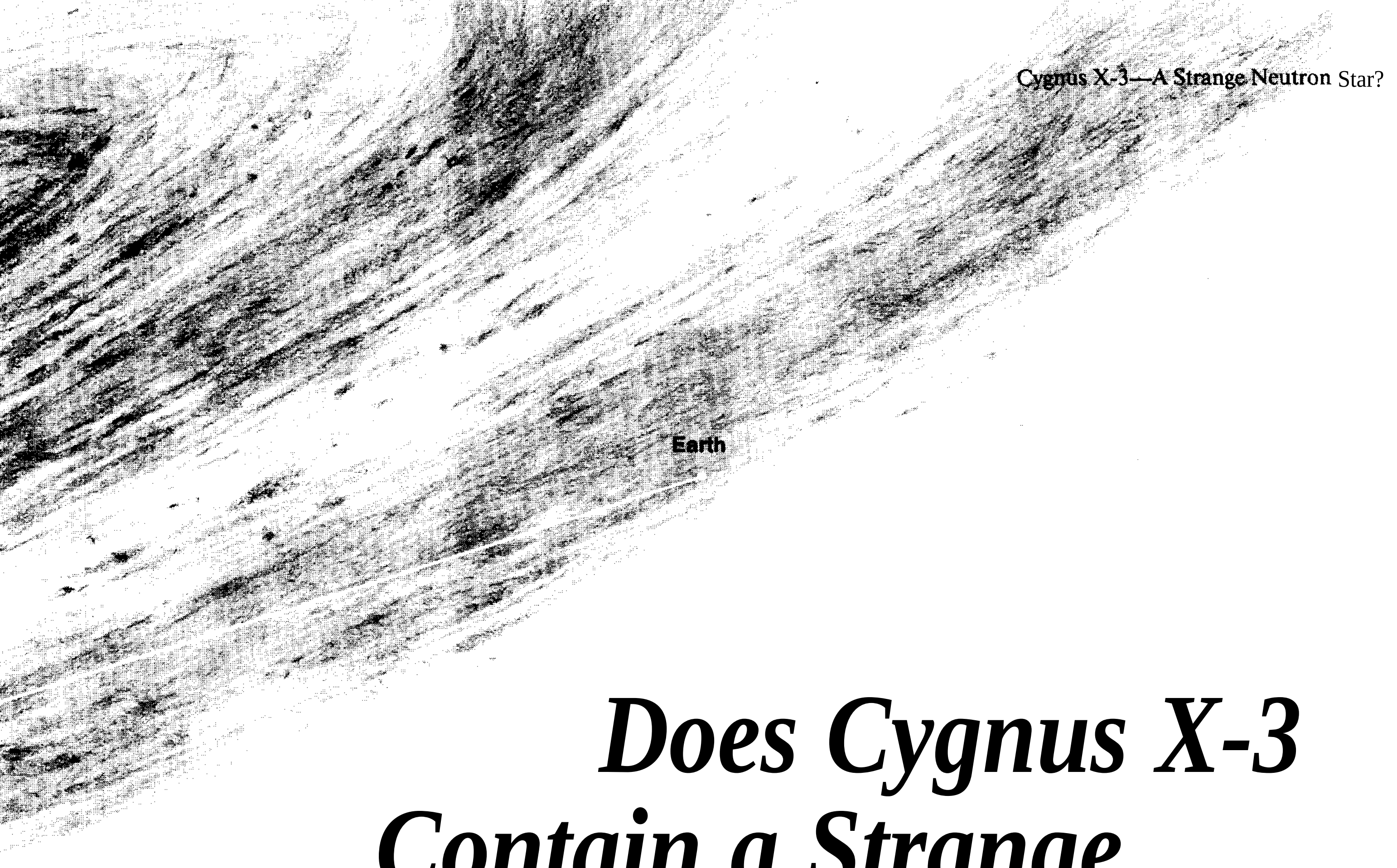
Cygnus X-3—A Strange Neutron Star?



Deep underground proton-decay detectors in the Soudan iron mine in Minnesota and under the Mont Blanc have recorded very energetic muons coming from the direction of Cygnus X-3 with its 4.79-hour periodicity. These observations, if confirmed, present a very challenging puzzle. What is the primary cosmic-ray particle that produces the muons at the earth, and how is such a particle produced in Cygnus X-3? One of the more coherent explanations is that the primaries originate as exotic hadrons (strongly interacting particles, not yet made in laboratories) chipped off the neutron star in Cygnus X-3, a star itself made entirely of matter containing a substantial fraction of strange quarks (Fig. 1).

The detection of a periodic muon signal deep underground constrains the properties of the primary. Firstly, its electric charge must be zero; otherwise the directionality and timing of the signal would be destroyed by galactic magnetic fields. Secondly, the mass of the primary must be less than its energy by a factor of about 10^4; otherwise differences in travel times of primaries with different energies would wash out the periodicity of the primaries and hence that of the muons. (A 100-GeV-mass particle, for example, would arrive about 1 hour sooner if it had an energy of 12 TeV than if it had an energy of 10 TeV (1 GeV = 10^9 eV and 1 TeV = 10^{12} eV).) To produce muons with sufficient energy to penetrate the overlying rock and reach the great depths of the detectors (equivalent to 2 to 5 kilometers of water), the energies of the primaries are likely to be in the range 10 to 100 TeV; the mass of the primaries is therefore likely to be at most 1 to 10 GeV. Lastly, the primary must have a sufficiently long lifetime, of order a year in its rest frame, that it not decay en route from the source. (Lorentz dilation increases the observed lifetime of a rapidly moving particle by the ratio of its energy to its mass.) The known neutral particles with such properties are photons, neutrinos, and neutrons, but arguments presented in the main text appear to rule these out. Briefly, the reported flux of muons is too high to be attributed to gamma rays (high-energy photons), the observed dependence of the muon flux on zenith angle rules out neutrinos, and neutrons would decay in flight unless their energy was unacceptably large.

The only remaining possibility is a previously unobserved particle, a ‘cygnet.’ The large flux of muons (comparable to the observed flux of gamma rays), and hence of cygnets, suggests that cygnets are



Does Cygnus X-3 Contain a Strange Neutron Star?

by Gordon Baym

Consultant to the Theoretical Division from the University of Illinois

made at a rapid rate through strong interactions rather than through the slower electromagnetic or weak interactions. One promising candidate for this strongly interacting particle is the *H* particle, earlier proposed by Robert L. Jaffe of MIT, composed of two up, two down, and two strange quarks in a closely bound state; the *H* is thus a particle with a strangeness of 2 and a baryon number of 2, the same quantum numbers as two lambda particles. If the mass of the *H* is less than that of the lambda (1.1 16 GeV) plus that of the neutron (0.938 GeV), then the lifetime of the ***H*** could be sufficiently long for it to be a candidate for the primary, since in this case it could not undergo the rapid decay into a lambda and a neutron. Decay of the ***H*** into two neutrons would be very slow since it involves a change in strangeness of 2, a rarer process than a change in strangeness of 1, as when a lambda decays into a nucleon.

How might cygnets be made in Cygnus X-3? To generate the high-energy gamma rays believed responsible for the extensive air showers observed, Cygnus X-3 must have an accelerator capable of producing charged particles with energies up to 10^{16} eV. Cygnets might be produced as the energetic charged particles accelerated from a neutron star interact with the atmosphere of the companion star. However, since the cross section for this process would have to be large to produce them in quantities comparable to those of the gamma rays, we would expect to have seen cygnets produced in laboratory accelerator experiments. (The cygnet mass should be relatively low, so the energy threshold for producing them should be well below the energies available at current accelerators.) A more likely possibility is that the cygnet is accelerated from a neutron star bound to charged particles in the form of an exotic nucleus. Free cygnets could then be released by fragmentation of such a nucleus when it strikes a particle in the atmosphere of the companion star, in a process similar to proton-nucleus fragmentation observed in the laboratory.

The next question is how exotic nuclei might be produced and emitted from a neutron star. A first possibility is that they are made by bombardment of the surface of the neutron star by particles accelerated onto it. (In the electromagnetic acceleration process electron-positron pairs will be produced, and if, for example, positrons are accelerated away, then the electrons will be accelerated back to the surface, at energies of a TeV or greater, and cause substantial spallation of the surface.) This

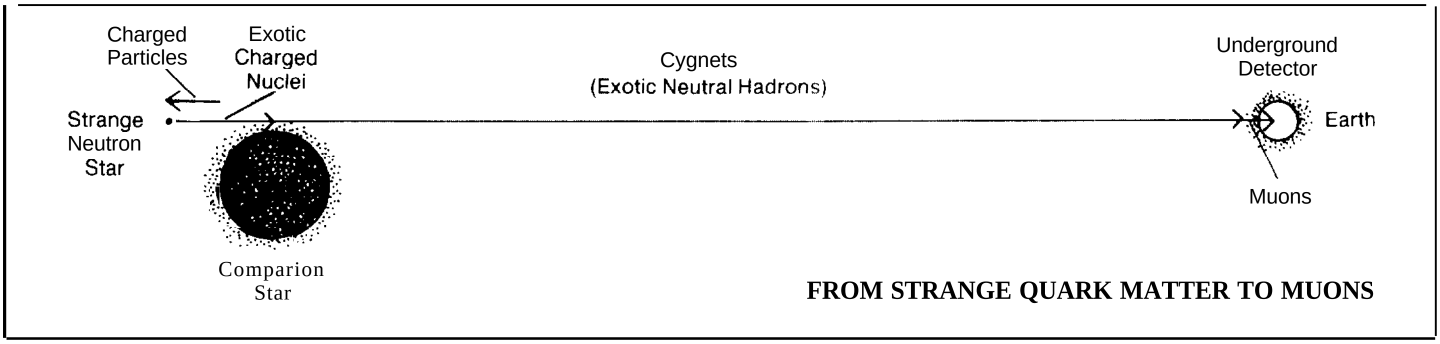


Fig. 1. A scenario for the observation, in underground detectors, of muons with the directionality and periodicity of Cygnus X-3. Particles accelerated onto the surface of a strange neutron star cause ejection of exotic charged nuclei, which are accelerated outward and fragment as they pass through the atmosphere of the companion star. The cygnets released travel undeflected to the earth's atmosphere, where they produce muons that penetrate to the underground detectors.

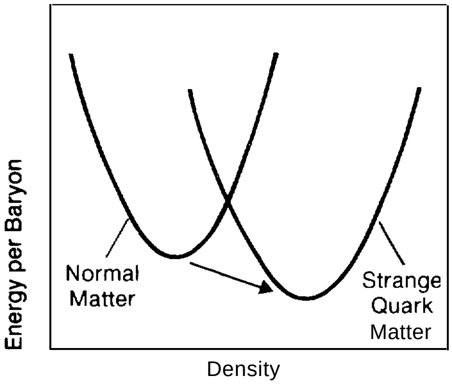


Fig. 2. If, as illustrated here, the minimum in the energy per baryon versus density curve for normal nuclear matter is higher than that for strange quark matter, then normal matter, which in its ground state sits at the minimum of the normal matter curve, would be unstable against transition to strange quark matter. This transition could result in a neutron star composed entirely of strange quark matter.

mechanism might produce exotic nuclei from normal nuclei, but one is faced with the question of why, if correct, it has never been observed in the laboratory. A second possibility is that exotic nuclei are produced in the core of the neutron star and then diffuse to the surface. But the lifetimes of the exotic nuclei must then be exceptionally long, at least the time required for diffusion, of order 10^5 years. The final possibility is that the entire neutron star is made of strange matter, and surface spallation throws exotic nuclei up into the beam of particles accelerated away from the neutron star.

Neutron stars may very well be made of matter containing a substantial fraction of strange quarks if, as Edward Witten of Princeton conjectured, the absolute ground state of matter might not be the familiar material nuclei are made of, but rather is 'strange quark matter' in which the quarks, a substantial fraction of which are strange, are not confined within individual nucleons but are free to roam throughout. By having less zero-point, or Fermi, energy, such matter could be stable compared to ordinary nuclear matter (Fig. 2). (We need not worry about ordinary nuclei turning into strange nuclei if strange matter is the lowest energy state only when a finite percentage of the baryons are strange.)

Imagine then a neutron star being formed (of normal nucleons) in the core of a supernova explosion. At the very high densities in the center (an order of magnitude above the density of laboratory nuclei, some 3 X 10^4 grams per cubic centimeter), a seed of strange quark matter can form either spontaneously or through a large density fluctuation. If the strange state is lower in energy per baryon than the normal state of nuclear matter, then once formed the seed will begin to convert the matter around it into strange matter, as a fire spreads through flammable material. The 'burning' front would first convert the liquid core of the neutron star to exotic matter; the heat ahead of the front would melt the crust of the neutron star, as well as melt the nuclei in the crust into normal fluid nuclear matter, and within an hour or so the entire star would be converted into a strange neutron star.

One important consequence of this scenario is that if the compact star in Cygnus X-3 is a strange neutron star, then many, if not all, neutron stars should also, as a result of the same burning process, be strange. Strange neutron stars are expected to cool more rapidly than normal stars since they can emit neutrinos more rapidly. This enhanced cooling should be observable in measurements with future x-ray telescopes of the surface temperatures of neutron stars.

The Cygnus X-3 muon data sugest the existence of a new and unusual particle produced in a new and unusual way. If future measurements confirm these data, the underground experiments will have led to a remarkable discovery of new physical phenomena. ■