Other messages from space

SOLAR NEUTRINOS

The Sun and stars maintain their energy output by nuclear fusion at their centres: a complicated chain of nuclear reactions, with the end result that H + H + H + H $\rightarrow$ He (4 protons $\rightarrow$ α-particle). This reaction releases a considerable amount of energy (nuclear reactions can liberate a few thousandths of the rest-mass energy of the initial particles – $E = mc^2$), but a good fraction of this output is in fact caried away by neutrinos, elementary particles with no charge and probably no mass; they would escape freely from the Sun, since matter is practically transparent to neutrinos. This creates a problem for their detection.

Several detectors, set up to look for these **solar neutrinos** are now operating, in USA, USSR, and Japan. The one at the bottom of the Homestake mine in South Dakota has been running over 25 years: in a 100,000-gallon tank of C_2Cl_4 (dry-cleaning fluid), absorbed neutrinos very occasionally convert a chlorine atom (Cl) to argon (Ar), which can be detected. N.B. Detectable neutrino fluxes are very small: the SNU (solar neutrino unit) is defined as 10^{-36} neutrino captures per target atom per second, and the observed flux at the South Dakota site is just two of these units.

Since this pioneering work, other experiments of this sort have studied neutrinos from the Sun. The GALLEX neutrino detector within an Italian mountain uses the Ga $\rightarrow$ Ge conversion. SUPERKAMIOKANDE is an underground cavern in Japan > 100 m across filled with water and lined with photomultiplier tubes (job security for research students); with such a colossal number of water molecules (10^{35}), a few rare Solar neutrinos do interact (tens of events per day). The reaction is inverse beta decay: $p + \nu \rightarrow n + e^+$. The positron takes up the neutrino momentum, and suffers relativistic recoil; this causes it to emit Cerenkov radiation, which can be detected on the walls of the cavern, and used to reconstruct both the direction of the initial neutrino and its energy (because the Cerenkov cone angle depends on the velocity of the positron). Designed as an experiment to detect proton decay, its huge mass makes it the most sensitive 'neutrino telescope' in the world. AMANDA will be a new kind of detector for high-energy neutrinos (from black holes etc.): neutrinos penetrating Antarctic ice will leave trails of Cerenkov radiation, to be detected by photon detectors buried in the ice [Sky & Telescope, July 1994]. ANTARES is a similar sort of idea, using several cubic km of Atlantic water off the coast of France.

The number of solar neutrinos found is only 30% of the number predicted by standard solar models. Is this because the astronomical models are wrong, or because our understanding of particle physics is wrong? This debate remains unresolved, but increasingly favours the latter possibility. Neutrinos come in three 'flavours', electron, muon, and tau neutrinos. An intriguing possibility is that neutrinos may 'flip' between the different 'flavours', so that we are looking for the wrong kind by the time they arrive at Earth. However particle theory says that this will only happen if neutrinos in fact have a very small but non-vanishing mass; the higher the mass difference between different neutrino species, the more rapid the oscillation between types. In order to explain the solar neutrino results, masses of a small fraction of an eV (energy units are used here: it means $mc^2 = 1$ eV) are needed. It is possible that the (so far undetected) tau neutrinos may be even more massive (just as the muon and tau particles are more massive versions of the electron). If the mass can reach about 10 eV, it is then possible that vast numbers of neutrinos spread throughout the universe could constitute the infamous dark matter.

SUPERNOVA NEUTRINOS

On 23 February 1987 a supernova (1987A) exploded in the Large Magellanic Cloud, a companion of our Galaxy. Simultaneously, and before the supernova was seen optically, the detectors in USA and Japan observed neutrino showers over a period of 10 seconds. Here was direct confirmation of nuclear processes in a catastrophically exploding star. The star's central temperature at that moment is estimated to have been 2×10^{11} K. The released energy must have been $\sim 3 \times 10^{46}$ Joules, which is about 10^{19} times the Sun's output in 10 seconds. The neutrinos carry away almost all of the energy, leaving only perhaps 1 part in 10^4 to power the fireworks. Even so, the supernova lay at a distance vast with respect to the Sun, and only a few dozen neutrinos were detected. No supernova has been seen within the Milky Way for about 400 years, whereas observations of many galaxies like our own suggest that the rate should be about one per century. It may be that we are overdue for a local supernova; it could also be that intergalactic dust in the Milky Way means that most supernovae go unobserved. In either case, the neutrino signal from a more nearby supernova would be very strong ($> 10,000$ detected neutrinos), giving us a wealth of information about the dying seconds of a star.

From the point of view of particle physics, it is significant that the neutrinos from SN1978A travelled the 160,000 light-years from the LMC and arrived at the same time, independent of energy. This limits their mass to below about 10 eV (otherwise the most energetic neutrinos would have travelled faster and arrived first).

GRAVITY WAVES

Accelerated mass should lose energy in the form of gravitational waves (a prediction of General Relativity). The argument is basically the same as for electromagnetic radiation: shaking lines of force should cause transverse displacements to propagate along the lines. The problem is that, except on the largest scales, gravitation is a weak force ...only 10^{-36} of the electrostatic force between two charged particles. A propagating gravity wave will cause a relative acceleration of bodies at different positions, but the likely size of any displacements is tiny.

Early (1970s) experiments by Weber in California, looking for vibrations in large rods, turned out to be mainly sensitive to the footsteps of passing students. Since then, experiments have become much more sophisticated. Today, the preferred technology for gravitational-wave detectors consists of two large suspended masses separated by distance L, where their relative separation is measured by means of laser interferometers. The UK's main group in this are is Glasgow University, which is part of GEO-600, an interferometer under construction in Germany, with $L = 0.6$ km. The USA is constructing LIGO, which has 4-km arms. Based on existing smaller interferometers, it is expected that these experiments will measure a fractional distortion of spacetime of about $\delta L/L \sim 10^{-19}$ to 10^{-20}. This is an absurdly small number, corresponding to being able to measure a shift in the position of one of the suspended masses of about the size of the atomic nucleus. The fact that it is possible is a tribute to what can be achieved by modern engineering. The most ambitious plan of this kind is for a space project called LISA, which would involve a network of 6 satellites in orbit around the sun.

However, it is not certain whether the current ground-based detectors will see anything, because their expected sensitivity is close to the expected effect for astronomical sources. Gravity waves are emitted most strongly from massive bodies undergoing high acceleration. The best we can imagine would be the coalescence of a pair of compact massive stars – a pair of neutron stars would be ideal. Such an event would yield a characteristic 'chirp' of gravity waves as the binary loses orbital energy (through its gravitational radiation) and merges into a black hole. The peak signal for this sort of event would probably exceed the above sensitivities, even for an event at cosmological distances. Since the preferred model for gamma-ray bursts is also the merger of a neutron-star binary, it is possible to imagine a wonderful future vision in which the gamma-ray and gravity-wave signals from a single event could be studied.

Astronomers don't like to wait, and most are already convinced that gravity waves have been detected. The reason for this is a special object called the **binary pulsar**. In fact, this is a single pulsar in orbit about a white dwarf, in a rather tight orbit (8 hours period). The existence of the pulsar as a natural clock means that we are able to use the Doppler shift to measure the orbit very accurately; what is found is that the orbit is speeding up, so that the 8-hour period is reduced by about 10^{-4} seconds per year (pulsar astronomy often shows this wonderful precision). This doesn't sound much, but the orbit is losing energy, and the observed rate is exactly what would be predicted from gravitational radiation. Therefore the interferometer experiments can be fairly confident that the waves they are looking for exist – and that detecting them will open up the study of the most exotic astronomical objects yet contemplated.

SETI

Astronomy provides no clear estimate for the probability of other Earth-like planets, let alone for the emergence of life, intelligence, technology ... and extinction. You can play games with

$$\boxed{\text{DRAKE'S EQUATION: } N = Rf_p n_e f_l f_i f_c L}$$

This says that the number of civilizations we should expect to see at any one time is the rate of creation of stars, times the fraction that have planets, times the number of planets per star that are like Earth, times the fraction of Earth-like planets on which life gets started, times the fraction of cases where life leads to intelligence, times the fraction of civilizations that can be bothered to communicate, times the length of time each civilization lasts. The only well-known number is R, although planet searches are now making progress with f_p; there's clearly a long way to go. Perhaps the biggest uncertainty is f_l, since the origin of life is a great mystery. Some influential people, notably Fred Hoyle, have argued that life originates in space [see Sky & Telescope, March 1994 and July 1997], and is spread throughout the galaxy by comets, so that $f_l = 1$. This may seem a far-fetched idea, but we saw that millimetre astronomy has detected complex 'organic' molecules; the trouble is, whether in space or on Earth, no-one understands how to get from amino acids to life.

Returning to Drake's equation, we don't even know that $N \geq 1$, since the equation gives the *expected* number of civilizations. This number might be so small that the probability of even one civilization in the entire universe would be very close to zero. Of course, we are here; but if we hadn't been, no-one would be asking any questions. It's possible that we are the cosmic equivalent of the winner of the National Lottery, and that there are no other intelligent beings anywhere. Alternatively, the universe might be full of them; to decide, we have to look.

In an attempt to settle the question, "Is anyone there?", NASA mustered sufficient optimism to commit modest funds to its 'Search for Extraterrestrial Intelligence'. The NASA-funded programme terminated in 1993, but is continuing as a privately-funded experiment (see the web address at the end of the notes). The SETI programme is based on radio telescopes, at several sites, in the frequency range 1 to 10 GHz, that can sample up to 14 million channels simultaneously. The favoured wavelength region is the 'water hole' where the cosmic animals come to talk: the range centred on $\lambda \simeq 10$ cm, where galactic and terrestrial radio background is minimal, cosmically 'advertised' by the presence of strong radio lines of H, OH, H_2O. There is a major computing problem in handling such a huge data rate and deciding when a 'signal' may have been received. Another way of searching might be to look for waste IR radiation from aliens' colossal astro-engineering projects. See Sky & Telescope December 1998.

An awkward question is going to be, when SETI has spent $100,000,000, and it's now AD 2002, and there's no positive result – what next? Perhaps L is very small ... if technology always leads to self-destruction ... who knows?

FURTHER INFORMATION

In addition to the articles mentioned in the text, the following books may be helpful if you are interested in following up any of the topics in more detail:

BURKE & GRAHAM-SMITH, An introduction to radio astronomy (C.U.P.)
CHARLES & SEWARD, Exploring the X-ray universe (C.U.P.)
LONGAIR, The New Astrophysics (in DAVIES (ed.) The New Physics, C.U.P.)
SMITH, OBSERVATIONAL ASTROPHYSICS (C.U.P.)
TIME/LIFE, The New Astronomy (in Voyage through the Universe series)

There is also a lot of interesting information (and spectacular pictures) available on the web. You may like to explore some of the following addresses:

http://www.ipac.caltech.edu
http://www.sdc.asi.it
http://sofia.arc.nasa.gov
http://wave.xray.mpe.mpg.de/rosat
http://chandra.harvard.edu
http://astro.estec.esa.nl
http://www.jb.man.ac.uk/merlin
http://www.ast.cam.ac.uk/Gemini
http://info.aoc.nrao.edu
http://www-sk.icrr.u-tokyo.ac.jp/doc/sk
http://www.ligo.caltech.edu
http://www.geo600.uni-hannover.de
http://www.seti-inst.edu/science/ph-bg.html