Neutrinos and Gravitational Radiation

Initial question: What can neutrinos and gravitational waves tell us about the universe that is not accessible via observations with photons?

Throughout this course we've focused almost exclusively on photons. This is reasonable for a radiative processes class, especially because virtually all information we have about astronomy comes from detections of photons in one way or another. For this final lecture, however, we'll take steps in other directions. More and more experiments are aimed at detecting qualitatively different types of radiation, and in particular we'll look at neutrinos and gravitational radiation.

Let's start with neutrinos. Neutrinos are produced when the weak force is involved in an interaction. **Ask class:** can they think of examples? Conversion of a proton to a neutron (or vice versa) involves neutrinos, so nuclear processes in the center of the Sun are an example, particularly hydrogen fusion, which requires eventual conversion of four protons into a helium nucleus of two protons and two neutrons. Another example is the neutronization that occurs during core collapse of a massive star. The conversion of a proton plus electron into a neutron is fundamentally driven by the rising Fermi energy of the electron, but in order to conserve various quantities, a neutrino must be involved. Let's examine this: in addition to energy, linear momentum, and angular momentum being conserved, we know that electric charge, baryon number, and lepton number must be conserved. Therefore, if we want to convert a proton into a neutron:

$$p \rightarrow n \tag{1}$$

we have to add things to either side. Baryon number is already conserved, so we have to worry about lepton number and charge. The proton is positively charged and the neutron is uncharged, so either a negative charge (e.g., an electron) must be added to the left side or a positive charge (e.g., a positron) must be added to the right. If this happens, though, then a compensating lepton with no charge must be added to the proper side, and this is where a neutrino comes in:

$$\begin{aligned} n &\rightarrow p + e + \bar{\nu}_e \qquad \text{or} \\ p + e &\rightarrow n + \nu_e \end{aligned} \tag{2}$$

are typical. Neutrinos are thought to carry most of the energy in a typical supernova and are primary indicators of nuclear fusion, so it would be wonderful to observe them.

Unfortunately, neutrinos interact very weakly. Typically, a neutrino of energy E_ν has an electron scattering cross section of

$$\sigma_\nu \approx 10^{-44} \left(\frac{E_\nu}{m_e c^2}\right)^2 \ \mathrm{cm}^2 \ . \tag{3}$$

This is what is technically known as an itsy bitsy cross section. Now, particle physicists have a lot of time and a fondness for alcohol, leading to interesting terminology and names for units. In this case, they've dubbed 10^{-24} cm^2 a "barn" and 10^{-48} cm^2 a "shed", so a typical neutrino cross section is some ten thousand sheds! This compares with the Thomson cross section, which is close to one barn; indeed, hitting an electron with a photon is like hitting the broad side of a barn compared to hitting an electron with a neutrino. For people without a sense of humor, 10^{-44} cm^2=10^{-48} m^2 is one square yoctometer. Pretty small, no matter how you slice it.

Let's figure out the fraction of neutrinos interacting in certain circumstances. First, the Sun. **Ask class:** to order of magnitude, what is the density of the Sun? About 1 g cm^{-3}. That means that the number density is about 10^{24} cm^{-3}. **Ask class:** so, what is the mean free path of $\sim$ 1 MeV neutrinos? About 10^{20} cm. The Sun is about 10^{11} cm in radius, so only a fraction $\sim 10^{-9}$ of the neutrinos interact.

Now let's think about the dense core in the center of a star just prior to a supernova. **Ask class:** if you crush the Sun down to a radius 1000 times less than it actually has, what happens to the optical depth to neutrinos? Density is $1000^3 = 10^9$ times greater, but the length traveled is 1000 times less, so optical depth is 10^6 times greater. That suggests an optical depth of about 10^{-3}. The neutrinos in supernova are actually somewhat more energetic as well, about 3–5 MeV, so a fraction $\sim 10^{-2}$ of the energy is absorbed. This seems to be enough to be the crucial driver of the supernova, since a good 10^{53} erg is released in neutrinos.

Sadly, this tiny cross section makes neutrinos really tough to detect! **Ask class:** what detection strategies could be used? The basic issue is that, since the probability of interaction is tiny, there have to be an enormous number of things with which the neutrinos can interact.

The first approach used (by Raymond Davis, co-winner of the 2002 Nobel Prize in Physics) was radiochemical. That is, he put 4×10^8 cm^3 of cleaning fluid (!) in the Homestake gold mine in South Dakota. The point is that cleaning fluid contains a lot of chlorine, and neutrinos can cause the reaction $\nu_e + {}^{37}\mathrm{Cl} \rightarrow \mathrm{e}^- + {}^{37}\mathrm{Ar}$, with a threshold energy of E_{th}=0.814 MeV. The Argon was chemically separated every month or so, and detected from ^{37}Ar decay. The point was to observe the neutrinos from fusion in the Sun and get direct information about those processes. **Ask class:** what drawbacks might there be to this approach? There is no information about time, direction, or spectrum of the neutrinos. It just gives a total number. This number, however is substantially less than predicted in a standard solar model with standard particle physics, and this has turned out to be a rather profound issue. As Elim mentioned in class, vacuum oscillations of neutrino flavors (which dominate below 5 MeV) and the density-dependent MSW oscillation mechanism (which dominates above 5 MeV), mean that there is a deficit in the electron neutrinos we can detect. More specifically, since only electron neutrinos are produced initially and are detected by this method, there's a deficit. More recent radiochemical methods use gallium: $\nu_e + ^{71}\mathrm{Ga} \rightarrow \mathrm{e}^- + ^{71}\mathrm{Ge}$, with a threshold energy of $E_{\rm th}$=0.2332 MeV.

A second method uses scattering directly. If a neutrino with high enough energy scatters off an electron in some medium, then Cerenkov light will be emitted if the electron has enough kinetic energy. Again, you need tremendous volume to do this. The largest-scale water tank of this type is the super-Kamiokande detector in Japan. The advantage of this method is that when the Cerenkov light is observed, it gives the direction and time of an interaction as well as the spectrum of the neutrinos. The disadvantage is that a neutrino with $E > 5 - 8$ MeV is needed, so the signal is weak.

A new generation of detectors looks for ultrahigh energy neutrinos, such as might come from gamma-ray bursts or some categories of ultrahigh energy cosmic rays. These use phenomenal volumes, e.g., the IceCube array in Antarctica has sensors placed deep in a cubic kilometer of ice. This ran into interesting challenges; for example, the background in the ice experiments was larger than initially thought, because the ice needs to be very uniform and this took deeper digging than had been anticipated. For deep-sea experiments it gets even weirder: the DUMAND experiment (Deep Undersea Muon and Neutrino Detector) had a substantial background from luminous deep-sea fishes! Still, there have been some impressive recent successes: the IceCube experiment detected 28 neutrinos above 100 TeV energy, including two above 1 PeV energy (named Bert and Ernie), and also has placed interesting limits on very high energy neutrinos from gamma-ray bursts.

If we detect neutrinos, what can we learn from them? Their low cross section means that using them, we can peer deep into events that would otherwise be opaque. For example, if enough neutrinos were detected from a supernova, with good energy and time resolution, this would add immensely to our understanding of such events. Around 10-20 neutrinos were seen from SN 1987A, which was enough to confirm that a neutron star had been formed (although fallback may have produced a black hole a few seconds later) and yield some constraints on the physics. Observation of $> 10^{15}$ eV neutrinos may test fundamental physical theories. Finally, some people have talked about detecting a cosmological neutrino background. Just as there is a 2.7 K photon background, there is expected to be a 1.9 K neutrino background. This would encode primordial fluctuations and be a snapshot from even before big bang nucleosynthesis occurred. **Ask class:** why might this be difficult? Since the cross section goes like E^2, we're talking about around 10^{-63} cm^2, which might be detectable with the Pacific Ocean but would otherwise be rather challenging!

See http://icecube.wisc.edu/science (the IceCube page at Wisconsin) for many details about neutrino astrophysics and the IceCube experiment.

Now let's talk about gravitational waves. For these, think about the standard general relativistic gravity analogy of a bowling ball on a rubber sheet. It dents the sheet, and if a second bowling ball is rolled past the first, the two will move around each other and create ripples that propagate away energy. In the case of real gravity, the ripples are distortions in spacetime that are called gravitational waves. Returning to the analogy, if you had a ball of a given mass that shrunk in place, the rubber sheet would dip more at the center but no waves would propagate out. If the ball just rotated axisymmetrically, then the nearby sheet would be dragged in the direction of the ball, but again in a time-stationary way there would be no ripples. Similarly, gravitational radiation is not emitted under conditions of spherical symmetry or axisymmetry. A time-varying quadrupole moment is needed (recall that for electromagnetism, a time-varying dipole moment was needed; the difference is that there are positive and negative charges, but not positive and negative masses).

What are potential sources of gravitational radiation? Any two objects orbiting around each other will do. So will a lump in an accretion disk, and there has been discussion of whether the conditions in the extremely early universe (e.g., the transition from quarks to nucleons, or inflation, or the Planck era) might generate gravitational waves.

The catch is that these are unbelievably difficult to detect. If a ripple in spacetime goes by, the result will be to change the measured distance between objects. The problem is, the change is really tiny: a strong gravitational wave will produce a fractional change in distance of around 10^{-21}, which is roughly the diameter of an atomic nucleus divided by the size of the Earth! Faced with such a challenge, one has to answer two questions: (1) how can you detect such a weak effect, and (2) is it worth the effort? We'll answer the second question first.

There are multiple reasons why gravitational wave detection will be worthwhile. One is that there are lots of events in the universe that are expected to be invisible in all other ways, including neutrino emission. For example, two black holes spiraling into one another emit only gravitational radiation. Another lure is that the gravitational radiation from merging compact objects will come closer than any other observation yet imagined to giving direct information about the behavior of strong gravity. A longer shot (in my opinion) is that gravitational waves may be the only way that ultra early universe models may be distinguished from each other, observationally. Inflation models may possibly lead to detectable gravitational waves from the early universe, but colliding brane models don't, at least currently.

Great, so how are these to be detected? The basic principle is you need something that is extremely sensitive to tiny changes in distance. Joe Weber of Maryland was a pioneer in this respect. He considered both bar detectors and laser interferometers. Bar detectors, which he built, are based on the idea that when a wave hits, resonant modes are detected in the bar. He reported a number of detections, but these were not confirmed and the signal strength would have had to be many orders of magnitude larger than is considered reasonable now. The majority of current effort is directed towards laser interferometers, which (by multiple reflections between mirrors) can be at the required sensitivity, for sources with frequencies $\sim 20 - 2000$ Hz. Real world effects make this challenging, to put it mildly. Earthquakes, trucks, mirror vibrations, nearby logging, ... make it pretty rough. On the longer term, space-based detectors (sensitive to frequencies of $10^{-4} - 10^{-1}$ Hz) would evade those problems at the expense of others (micrometeorites, synchronizing the orbits of satellites five million kilometers apart to within a few millimeters, etc.!). Another detection approach that might be a few years away involves pulsars: if there is a background of gravitational waves due to (probably) orbits of supermassive black hole binaries, there could be subtle timing residuals in the pulses from millisecond pulsars. These would be most sensitive at lower frequencies, on the order of $10^{-8} - 10^{-6}$ Hz. It is likely to be five years or so before gravitational waves are detected directly. However, there is no real doubt that they exist, because timing of binary pulsars has confirmed the loss of energy and angular momentum expected from general relativity to a part in a thousand.