Current Research in High-Energy Astrophysics

High-energy astrophysics involves phenomena in rather extreme physical situations. These include ultrastrong magnetic fields (up to 10^{15} G), strongly curved spacetime (such as near the horizon of a black hole), extremely dense matter (up to several times nuclear density), and particles with energies a billion times what can be achieved in terrestrial laboratories. This means that high energy astrophysics can reveal not just interesting things about astronomy, but can help us probe fundamental physics as well.

In this class we will explore some of the phenomena that generate high energy photons and particles, meaning relativistic particles and photons in the X-ray range and above. These include black holes, neutron stars, gamma-ray bursts, and the generation of ultra high energy cosmic rays. To understand these we will first get a grounding in the relevant basic physics, including the interactions and generation of high-energy photons and particles, their detection, and general relativity. We will then go over the sources themselves and some of the phenomena observed from them. These include black holes, neutron stars, and clusters of galaxies. As we discuss each source, we will first go through the basics and then discuss current frontier areas of research. For example, active research is proceeding on how to detect signatures of strong gravity from black hole sources; how is this done? What are people doing with respect to detecting evidence of ultrastrong magnetic fields? What produces cosmic rays above the so-called "GZK cutoff", where the cosmic rays were expected to be attenuated rapidly? What causes gamma-ray bursts?

Developing Astrophysical Reasoning Skills

As discussed in detail in the "Hints about doing research in astrophysics" file on the class web page, there's quite a transition between classwork and research. In this course I will encourage development of research-oriented skills. One of these is the ability to size up a problem and determine how best to approach it, given the goal of the research and the needed accuracy. Some things are best solved analytically and some with a computer; some require great accuracy and some are best done with order-of-magnitude estimates; and so on. In all cases, though, you've got to be able to sit back and ask yourself "Does this make sense?" so that a programming bug doesn't convince you that energy isn't conserved!

One aspect of "does this make sense" is that you need to be able to look at a result and determine if it satisfies several "common-sense" criteria, from simple to complex. Does it have the right units? Is it correct in limits that I can check easily? Does it possess the appropriate symmetries? Does it depend on what it should depend on, and no more? Ideally, you should do this before you embark on a calculation, and also afterwards, to check your result. You'd be surprised at how often you can catch errors this way or sharpen your intuition. Here's an example, due to Doug Hamilton:

Units, Limits, and Common Sense

You launch a rocket straight up from the Earth's North pole, and it rises up to a maximum height H, then falls back to Earth. The maximum height above the Earth is given by one of the expressions below. Here R_E is the Earth's radius, $X = v^2 R_E/GM_E$, G is the gravitational constant, M_E is the Earth's mass and v is the launch velocity. Without solving the problem, rule out as many of the incorrect equations as possible using simple physical arguments.

A) $H = R_E X/(1+\sqrt{X})$
B) $H = R_E X/(1-X)$
C) $H = R_E X/(2-X)$
D) $H = R_E(1-X)/(2-X)$
E) $H = vX^2/(2-X)$
F) $H = R_E X/2$
G) $H = R_E X^2/(2-X)$
H) $H = R_E X|1-X|/(2-X)$

You can rule out all but one of these possible answers using relatively simple arguments. This means a huge savings in time, and if you get in the habit of thinking about answers in this way your intuition will improve dramatically.

Simplification of equations

A separate skill that is often useful is the ability to examine a problem and determine what complications can be dropped and yet retain the essence of the physics or at least the desired accuracy. Here's one example. Suppose you have a photon with energy $\hbar\omega$ scattering off an electron at rest. The total cross section, with $x \equiv \hbar\omega/m_e c^2$, is

$$\sigma = \frac{3}{4}\sigma_T \left\{ \frac{1+x}{x^3} \left[\frac{2x(1+x)}{1+2x} - \ln(1+2x) \right] + \frac{1}{2x}\ln(1+2x) - \frac{1+3x}{(1+2x)^2} \right\} . \qquad (1)$$

Looking at such an equation, I don't feel any surges of intuition! Moreover, in many circumstances where this result might apply, there are other uncertainties in the problem that make unnecessary accuracy superfluous. In such cases, you could approximate by assuming that for low-energy photons, $x < 1$, the cross section is the low-energy limit of this expression, which is just $\sigma = \sigma_T = 6.65 \times 10^{-25}$ cm^2, the Thomson cross section, and that for $x > 1$ the cross section is the high-energy limit, $\sigma \approx \frac{3}{8}\sigma_T x^{-1}(\ln 2x + 0.5)$.

Here's another example, from last year's ASTR 688R midterm:

Suppose that low-mass stars ($M < M_\odot$) have a uniform density equal to that of the Sun (ρ=1.4 g cm^{-3}) and a central temperature

$$T_c = 2 \times 10^7 \left(\frac{M}{M_\odot}\right)\left(\frac{R}{R_\odot}\right)^{-1} \text{ K} . \qquad (2)$$

Suppose also that the stars are pure hydrogen ($X = 1$), and that the main reaction burning hydrogen to helium has an energy generation rate of

$$\epsilon_{\rm eff} \approx \frac{2.4 \times 10^4 \rho X^2}{T_9^{2/3}} e^{-3.38/T_9^{1/3}} \, {\rm erg\,g^{-1}s^{-1}} \,, \tag{3}$$

where $T_9 = T_c/10^9$ K. Stars stay on the main sequence until they have exhausted most of the hydrogen in their cores, which we will assume have a uniform temperature equal to T_c. To within a factor of 2, calculate the mass of the lowest-mass stars, which have main sequence lifetimes of $\sim 10^{13}$ yr.

Answer: Now, this looks like a killer equation. If you tried to solve it exactly you'd need a computer. However, if you have the insight that the burning rate is extremely low and that this implies that the exponential must be very small, you have a dramatic simplification open to you. In particular, to the required accuracy you can drop the power-law prefactor (!) and treat it as simply an exponential equation, which is trivial to solve. To get the numerical answer you also need to know the energy released by hydrogen burning, to get the energy generation rate. In any case, a nasty problem is solved simply and the insight is retained, by just making an easy simplification.

Approaches to Creativity in Astrophysics

Creativity can be said to have two steps: (1) coming up with a list of possibilities, (2) going through those and throwing out what doesn't work, to focus effort on the more promising explanations.

Let's say you want to explain a phenomenon. One approach is to simply make a big list of anything you can think of that might explain it (without culling them at this stage), then later go through the list and see if observations or other constraints absolutely rule out some of the proposals. Doing it in a two-step way like this gives you a chance to come up with something really original (by not cutting it down first), but also serves as a check against errors.

To do this successfully, you need to have a wide range of knowledge of physics and astrophysics, both to generate ideas and to test them. In this class we will try to generate a set of tools to approach problems in high-energy astrophysics, so that we can come up with ideas and cull them for the most promising.