QnAs with Steven A. Balbus

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In early 2016, Oxford University astrophysicist Steven Balbus was filling in for a colleague, teaching a course on general relativity. Although not an expert in relativity before the course, Balbus felt growing admiration for Albert Einstein's century-old theory. In February, during the course, Balbus and others around the world heard news out of the Laser Interferometer Gravitational-Wave Observatory (LIGO) that a clear signal of gravitational waves, described theoretically by Einstein, had been detected. The waves were thought to emanate from the merging of two black holes, and the discovery opened exciting possibilities of using gravitational waves to observe astronomical phenomena, much as light waves are used to observe astronomical objects through telescopes. Balbus, elected to the National Academy of Sciences in 2015, thought that the textbook method for deriving gravitational wave equations contained a level of mathematics that could be daunting to some students. His Inaugural Article puts forth a streamlined derivation (1). Balbus recently spoke to PNAS about his work.

PNAS: How has the discovery of gravitational waves changed the world of astrophysics?

Balbus: It's early days yet. After 45 years or more of development, the technology actually works as advertised. These interferometers, which can measure deviations of 1/10,000th of the size of a proton, are actually performing up to and in some cases in excess of specifications. At the technical level, it's amazing.

Although there was ample evidence before, we finally have an absolute smoking gun here for the existence of black holes. There's simply no way to explain [these] data unless our theory of black holes is correct.

PNAS: How did you feel personally when you heard that news from the LIGO laboratory?

Balbus: It was very emotional. I knew how difficult it was, and I knew how important it was. This has been a field where there have been a lot of ups and downs. So to see it reach fruition and not only work, but work beautifully—the signal was almost straight out of a textbook. It's so clean, it left absolutely no doubt. It was just such a beautiful moment.

PNAS: What are some of the exciting possibilities that the discovery of gravitational waves open in astrophysical research?

Balbus: What we can do now is study black hole binary systems. Not every star forms a black hole. A black hole binary would have to form from a binary system with two objects massive enough not just to go to white dwarfs or neutron stars, but to evolve all of the way to black holes. So how often does that happen in our theories of star formation? How often do these massive binaries form?

One of the speculations is that asymmetries that are associated with supernova explosions would produce their own form of gravitational radiation. So that's another area where people are excited that they might actually have a diagnostic, which would be something very novel, and something of course that's not been used before. The other domain of extreme opacity is the early universe itself. There the sources are deviations and asymmetries of the background metric for the universe, which manifest themselves as gravitational radiation, so this is another area of exciting possibilities for making progress.

I'm not a relativist by training. Most of my work is in the subject of astrophysical fluid dynamics. So I've worked on accretion disks, the interstellar medium, and the interiors of stars. It's been a lot of fun to work in a new field like this, because it is quite different from what I have done before. If a year or two ago you had asked me what my Inaugural Article (1) would be, I would never have guessed that it would be a paper on general relativity. This really is a new era for astronomy and like all breakthroughs of this magnitude in the past, it is almost impossible to foresee where it will lead.

Steven A. Balbus. Image courtesy of © The Royal Society.

This is a QnAs with a recently elected member of the National Academy of Sciences to accompany the member's Inaugural Article on page 11662 in issue 42 of volume 113.

PNAS: The equation you derived for the course and for your Inaugural Article (1) is for a stress-energy tensor term. What is a stress-energy tensor?

Balbus: Physicists deal with different kinds of mathematical objects in their equations. There are ordinary numbers, or scalars, like temperature and mass. There are vectors, which have not only a magnitude but also a direction. Other quantities require not just one but two directions. The stress-energy tensor is like that. It's a table of numbers where you write down key quantities that appear in Einstein's equations. It's this mathematical object that gives rise to all of the manifestations of gravity in Einstein's theory.

The question is: What is the stress-energy tensor that is associated with a gravitational wave itself? Historically, that has been a difficult problem. Conceptually, it's difficult because waves are part of the curvature. They're not a source of the curvature the way the ordinary matter stress-energy tensor is, but part of the curvature response. However, you need to think of these waves as an effective energy somehow if you're

going to calculate, in a practical sense, what the energy loss is from a binary system.

There's a way now to do this that's discussed in textbooks, where you take the curvature side of the Einstein equation, and then you take only a certain part of it and regard that in isolation as the wave stress energy, or how much energy is being carried off in the wave. When you try to do this for beginning students, it's confusing. Not very many of them are able to take it in.

I found a way to calculate how much energy is being carried off by the gravitational wave, and in addition not just the energy but all of the other stuff that is carried by the gravitational wave, its angular momentum, and so forth. I found out a way of doing that in just a few lines, working with the fundamental wave equation itself. The result that I wrote up in this paper (1) is in complete agreement with standard theory, but the route to it is a much simpler one.

PNAS: Is your intention that teachers use your simple derivation to introduce students to gravitational wave principles?

Balbus: That would be my fondest hope.

¹ Balbus SA (2016) Simplified derivation of the gravitational wave stress tensor from the linearized Einstein field equations. *Proc Natl Acad Sci USA* 113(42):11662–11666.