Podcast interview: Brian Fields

PNAS: Welcome to *Science Sessions*, the podcast of the Proceedings of the National Academy of Sciences, where we connect you with Academy members, researchers, and policymakers. Join us as we explore the stories behind the science. I'm Paul Gabrielsen and I'm speaking with Brian Fields of the University of Illinois at Urbana–Champaign. In a recent PNAS article, he and his colleagues explored a hypothesis that mass extinctions at the end of the Devonian Period, around 359 million years ago, may have been caused by supernova explosions.

So I wonder if you could start by telling us what the world was like around the end of the Devonian Period. What animals might have been present then that we might be familiar with today?

Fields: So, I just wanted to thank you for the opportunity to do this. This is work that we were very excited about, and I'm thrilled to get a chance to share. And I should also be clear that my background is astrophysics. So, the Devonian spanned some 60 million years of time from about 419 to 359 million years ago. And the world was really a different place then.

So the globe itself looked nothing like it does today, the continents on the globe. In fact, the continents were coming together to form Pangea, you know, the, sort of, single continent. That hasn't—hadn't happened yet, but it was on its way. And the globe then was dominated by the super continent called Gondwana and other small continents, including Siberia, that would soon merge together with it. So the geography was very different and the inhabitants were very different. And so in the oceans, life was already quite abundant, and creatures that we would recognize, but probably not want to meet, would be sharks, which are already present in a primitive form. And there also were the first ammonoids, which are a type of cephalopod of which today an example would be an octopus. So things like that.

And this was also an age when the fish first flourish throughout the oceans. And one other sort of well-known kind of photogenic marine species were the trilobites, which was sort of small horseshoe crab–looking critters. Then what about the land? Well, the Devonian was a time when life was really taking hold on land. Forests covered the continents with trees that were 30 meters high, but actually more closely related to mosses than to modern trees. And on land there were early insects. We would recognize spiders and millipedes. And there, most importantly, were four-legged creatures called tetrapods—four legs—which had risen up out of the water and began to walk on land. And we should look on those critters with respect because we are the descendants of their survivors.

PNAS: So now tell us what we know about the scale of the mass extinction at the end of the Devonian.

Fields: So the Devonian is counted among the big five mass extinctions. So there are five really big, devastating wiping-out of species in geological–biological history. The most recent mass extinction that's famous and everyone knows is when the dinosaurs died out 65 million years ago. So the Devonian was 360 million years ago, so much further back. And it is rightly counted among the big five, but it's different from the others in that it's less sudden; rather there was a long decline, punctuated by several dramatic extinction events.

The last years of the Devonian were a long stretch of time that was challenging for life. So even under normal conditions some species are always dying out, but usually new species rise to take their place. But in the last 10 million years or more of this period, there were very few new species appearing, leading to fewer species alive. That is, less biodiversity. And why is that?

Well, as I understand it, the reason for this diversity crisis is likely related to the coming of Pangea—the converging of the continents—as well as the rise in sea level. Both of these meant that there was less geographical isolation and so less opportunity for species, you know, to sort of quarantine themselves, as we might say, and diversify themselves. So the diversity decline was happening already for terrestrial reasons, and that's not due to a supernova; but, in the final million years of the Devonian, there were some events of rapid extinction. And the very last of these is called the Hangenberg event. It occurred 359 million years ago, and it marks the end of the Devonian Period, so the boundary with the next period called the Carboniferous. And this is the time that most interests us because new research just out this year shows that during this last event, this Hangenberg event at the very end of the Devonian, there was a catastrophic loss of ozone in the Earth's atmosphere.

PNAS: So with that drop in ozone, what led you to suppose that a supernova may be responsible? What are the alternative plausible triggers?

Fields: Sure. And that's an important point that; we don't yet know what caused the ozone loss. And so this Southampton group that found the evidence for the ozone loss, they themselves thought about where it could come from and considered a couple of explanations. So one is volcanism. So if there is an increase in volcanic activity, then gases from the eruption could be damaging to ozone. But, the Southampton group found that there was no evidence of increases in the element mercury that also comes from volcanic explosions, so it looks like that's probably not the culprit. So instead, they looked for another explanation for ozone loss, and they propose that it might be caused by global warming, which is occurring about the same time. And this is absolutely an interesting idea and deserves more study, not the least of which is because we're now in an age of global warming and it'd be important to know if that could also damage ozone.

And then turning to our idea. So what we wanted to do was to bring attention to the fact that there's a whole other set of possible explanation for global catastrophic ozone loss, and that's from astronomical explosions, explosions in space. So it turns out the cosmos can sometimes be a dangerous place, particularly if you happen to visit a rough neighborhood. But the thing about most astronomical explosions is they tend to hit us all at once with one mighty punch. Then the Earth regenerates its ozone, and whatever survives tries to get on with life. But the geological record shows that the end Devonian—the extinction, this last extinction event—lasted for certainly many thousands of years. It's hard to say exactly how long, but certainly thousands of years. So a one-and-done event that's over in 10 years, that doesn't work. And that's what led us to narrow down the astronomical threat to that of a supernova.

PNAS: What exactly is a supernova? How does it affect the space around it?

Fields: Ah, very good. So, simply put, a supernova is the explosion that marks the death of a star. And in fact there are two main types, but let me focus on the most common type, which is the kind we think is the culprit. So the most common type of exploding star is what marks the death of the most massive stars. So I'm talking about stars eight, ten times the mass of the sun, or even more massive than that. And so, like all stars, massive stars are powered by nuclear fusion. That is, at the very heart of the star and the core of the star, it's under extremely high temperature, high pressure, and atomic nuclei collide and combine in nuclear reactions to make ever-heavier elements. And these same nuclear reactions also liberate energy that keeps the star nice and hot and pressurized. And that's good because this pressure is needed to hold the star up against its own gravity because, of course, the star is pulling in on itself in addition to other planets it might have.

The result of this is that stars are nature's alchemists. They're where new elements are formed, but, at the end of their lives, the star sort of runs out of fuel in the sense of their cores eventually make iron and nickel, which are the most stable mixture of elements there are from the point of view of nuclear physics, and they no longer act as fuel. They no longer can generate heat. That leads to instability and the star collapses. The core of the star is crushed to enormous density and then rebounds and explodes. And we see this happen. We see exploding stars across the cosmos, and when they explode, among other things, we see the new elements they make in the debris that they fling out into the cosmos because indeed 90% of the mass of the star is eventually ejected in the explosion. And initially the material flung out is moving very fast—a few percent of the speed of light.

PNAS: How would a supernova affect Earth's atmosphere?

Fields: Right. So when the explosion happens, the damage occurs in a couple of phases. So initially when the star explodes, it's very bright, and if the explosion we're talking about at the end of the Devonian, if that happened the way we think, at the kind of distances we're talking about, the supernova at its brightest would be brighter than the full moon. And that would last for months. So that means that you could see it easily during the day, which would be very impressive. But along with the light that you can see, the supernova also emits much nastier stuff: so ultraviolet radiation, x-rays, and even gamma rays—so very powerful light, high-energy photons. And those arrive initially with the explosion, and some of them arrive for the following months and year, the first year after the explosion. All of that very high energy radiation is ionizing. That is, it damages the atmosphere, and, in doing so, what it does is it destroys the ozone in the atmosphere; the ozone shields us from that radiation.

But in shielding us, the atmosphere is grievously damaged by losing this ozone, which is shielding us not only from the supernova, but always is shielding us from the sun, and then the ultraviolet from the sun can damage the Earth. Nowadays, we've had this problem of an ozone hole. I'm not talking about an ozone hole, I'm talking about wiping out the ozone layer. And with that gone, there's intense ultraviolet radiation, which is bad for life. And so creatures and plants on the surface of the Earth and at the very top of the water in the oceans would be harshly damaged. You and I would put on our sunblock and a hat, but if you're a small plant, a small animal, or a phytoplankton, there's nothing you can do about it. And the problem is those things are at the bottom of the food chain. But we're not done. The supernova has a one-two punch. So this blast of material from the supernova, remember, ejected 90% of its matter. And that material sweeps through space collecting any matter between the supernova and us and builds up into this blast wave. And eventually this blast wave overcomes the Solar System and envelops the Solar System. This blast wave acts as a particle accelerator. We see this happening in supernova remains that they accelerate particles to high energy. These are called cosmic rays; we get them all the time at the Earth, but they'll be very intense when the supernova hits us because we're sitting right at the particle accelerator and those cosmic rays will irradiate our atmosphere.

And the result of that is, first, that will again remove the ozone from the atmosphere. And then there also will send high-energy particles, called muons, that come all the way down to the ground and even go half a mile underground and into the water. And so this is how to get an extended period of extinction.

PNAS: So what damage would the radiation have done to the living organisms of the time?

Fields: Exactly so, and there are several effects. There's sort of direct and indirect effects. These muons, like I said, they go straight through our heads. They're hard to stop. They don't just stop at the surface, like ultraviolet radiation. They can go down half a mile before they finally get stopped.

And so they literally are delivering radiation, which is damaging to organs and to DNA, so they can cause mutations and cancer. And in fact, we have cosmic rays even bathe the Earth now, but they'd be much more intense due to a supernova. And it would likely overwhelm the ability of species to, sort of, correct for this damage. And they're likely to be the most damaging to large creatures, sort of sometimes called megafauna, with big volumes. So they'll be, you know, hit by a lot of cosmic rays.

So those are sort of the direct effects, but there also are indirect effects. Cosmic rays could likely affect the atmosphere and climate in various ways. So even today, cosmic rays are linked to lightning strikes. And so with very high doses of cosmic rays bathing the Earth, we'd expect more lightning and then possibly more wildfires, which would leave signatures we can hope to look for. And also the irradiation of the atmosphere creates various chemical reactions, including producing nitrates, which would rain out. And these basically act as fertilizer, nitrogen is a good fertilizer. And so there could be actually some sort of promotion of some species due to the sort of fertilizer effect.

PNAS: Is there evidence that such a star may have been at the right place at the right time to serve as the extinction trigger?

Fields: Ah, very good. So unfortunately, because we're talking about something 359 million years ago, not only has the world changed a lot, but our galaxy has changed a lot in that amount of time. In fact, that's enough time that, like most every other star in the Milky Way, we orbit around the center, and the Devonian was so long ago that the sun has made almost two orbits around the Milky Way since the Devonian extinction happened. So the stars have rearranged themselves considerably. As a result, we can't look around today and see any evidence for the supernova. One thing we can do, which we mentioned in our paper, is we can say something about the likelihood of having a nearby supernova. And the answer is we have something like probably three explosions per century in our entire galaxy, which is quite large.

And most of them are quite far away. And in fact, most of them are obscured by the soot and debris in interstellar space in our galaxy. So that in historical times, the bulk of supernovae in our own galaxy were not even seen by people because they were obscured. But based on what we know now, we can estimate the likelihood of having a supernova over this kind of timescale. And that's a perfectly plausible thing.

And nowadays, we can look around and it's very easy to find the massive stars because they put out more light than any other stars. Nearby massive stars are the brightest ones in the sky. And we know exactly where they are, and none of them are anywhere near the sort of kill distance. There are no supernova threats menacing us right now. But if you take a bigger view: think about your ancestors or your descendants over millions-of-years timescales, that's when you need to think about these things.

PNAS: How can we know if this hypothesis is right?

Fields: That's exactly the right question, and that was the other reason we wrote the paper: to not just propose the idea, but to suggest tests for the idea. And some of the tests are geological; that is, going to the geological records and looking for the expected effects of a near supernova explosion. There also should be radiation by cosmic rays. Which I said, for example, could lead to lightning strikes and wildfires, and those could leave indications in the fossil record. And like

I said, they could introduce nitrate production, which you could hope to see, and see evidence that it acted as a fertilizer.

And also in the patterns of extinction. So if these muons, which reach deep into the ground and into the water column, if they're really dangerous, then that should have particularly damaging effects to large creatures, these megafauna. And we can look for that as well, and look for mutations that these could cause.

If we find evidence of fires or if we find evidence for mutations, any given one of these things can be explained in other ways. So I think to really have a convincing picture of a nearby supernova will require an accumulation of evidence to discriminate this idea from other ideas for what could be going on to cause these extinctions. But there is one possible way to find the supernova that I'm particularly excited about. And it's very difficult, but it could provide the definitive evidence. And that is to look for supernova debris that has been delivered to the Earth.

So remember, I said most of the mass of the supernova is ejected into space. And I also said a supernova is an element factory. And when in the blizzard of nuclear reactions in these exploding stars, they generate all kinds of elements and most of them are stable, but some are unstable, which is to say radioactive.

And so when the supernova blast arrives in the Solar System, some of these radioactive species in minute amounts will literally rain upon the Earth. And we can hope to then look into the geological record, and, with very, very sensitive measurements, we can hope to find small traces of radioactivity that came from the supernova. And we have two kinds of radioactivity in particular—that is, two particular kinds of unstable atoms: One is a version of plutonium called plutonium-244, and another is a version of the element samarium called samarium-146. So why are we so interested in radioactivity? And so a nice analogy is with green bananas.

So here in the great state of Illinois if you happen upon green bananas, then you know two things. You know that they had to be made recently, cause they're still green. And, they somehow had to be brought here because, [in] Illinois, we don't grow bananas. And so radioactivity is kind of like this because bananas decay and radioactivity is about atoms that decay. So if we can find, in Devonian samples, we have radioactive plutonium or radioactive samarium, they're like green bananas. We know that they should decay, but if they haven't decayed yet, that means they had to be brought. They had to be recent; they can't be back from the formation of the earth; and they had to be brought here; and that points to a supernova. So that would be the smoking gun.

PNAS: Where could we find those radioactive isotopes?

Fields: Plutonium is, in some sense, easier to find, or at least really less incredibly challenging to find because the Earth doesn't naturally contain any plutonium at all; all forms of plutonium, all the different isotopes of plutonium, are all radioactive. And if there were any, when the Earth was born, they're long since gone and the Earth doesn't make more. If we find that at the Devonian, it’s very suggestive of a supernova; but then we'd want to follow up and look at the isotopes as well. And if there is plutonium at that time, it's likely to be taken up in the bones of the critters that were living there—in very minute amounts the plutonium itself wouldn't hurt them—but also in shells, so we can hope to look there. The downside with plutonium is: first, the supernova might not make it; but another thing is, you do have to be a little careful because there's no natural source of plutonium, but there are man-made sources of plutonium much more recently. So if we do find plutonium, it will be important to measure the isotopes because the isotope signatures are very different between a supernova and some of these sort of artificially made plutonium. So we can really tell the difference.

PNAS: Why is it important to know if the supernova hypothesis is correct?

Fields: Yes, indeed. And it's great that you use the word hypothesis because that's in fact what our paper is about. Our paper wasn't a proof that we had a nearby supernova. It proposed an idea that maybe this occurred.

And as Earthlings, we all have a stake in that answer. And indeed, even if we don't find evidence for a supernova, even if we ruled this out, this tells us something interesting and a bit surprising that either these kinds of explosions—which definitely occur—either they're rarer than we thought or maybe less dangerous than we thought. That would be good to know. If we indeed confirmed that this was a supernova, that has broader implications, for example, for the habitable region of our galaxy. So we live in this galaxy of stars, but it turns out supernovae don't explode evenly.

There are more supernovae more frequently closer to the center of the galaxy than out here, where the sun lives in the suburbs. So it might be that life can't exist near the centers of galaxies because it's a rough neighborhood. But my hope is that life is tougher than that, that it learns to adapt. And so if you live in a rough neighborhood, you're just forced to be resilient. And also, if we show that the end-Devonian was caused by a supernova, we can learn something about the supernova itself from the ashes it leaves behind. So if we find plutonium, it tells us a supernova made plutonium—which would be good to know—and we'd find out how much; that'd be super interesting to know.

And so we would be using these fossils as telescopes where dead critters from 360 million years ago tell us about the workings of exploding stars. I think it's good to step away back and think about the big picture, which is, of course, what astronomy nudges us to do anyway. So to me, the overarching message here is that life on Earth does not exist in isolation. We aren't just citizens of our little town or our state, or even our country. We're citizens of the cosmos as a whole, and the cosmos intervenes in our lives. Often, mostly, it intervenes imperceptibly; we don't even notice. But once in a while, we think, the cosmos intervenes ferociously.

PNAS: Thank you for speaking with me today.

Fields: No, no, my pleasure. Thank you.

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