*Dave Eicher:* Welcome to the Superstars of Astronomy podcast from *Astronomy* magazine. I'm Dave Eicher, editor-in-chief of *Astronomy*. Each month, I'll share the thoughts and research of the world's greatest astronomers, astrophysicists, cosmologists and planetary scientists with you in these hourlong chats.

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And I'm very excited today to have a distinguished guest for our seventh show, Bruce Balick. Among other things, Bruce is one of the greatest authorities we have on planetary nebulae, the end-state of stars like the Sun. He is professor of astronomy at the University of Washington in Seattle and has worked on a great range of topics, including star formation, active galactic nuclei, neutral hydrogen and early-type galaxies, and modeling and understanding, of course, the dynamics of the whole range of planetary nebulae.

Bruce decided he was interested in astronomy at a very young age and has never looked back. We'll discuss all of his areas of interests and research today. So without further ado, Bruce, thank you so much for joining me today.

*Bruce Balick:* It's an honor to be interviewed, and I'd like to welcome the entire audience. I wish I could meet all of you.

*Dave Eicher:* Well that is fantastic. And I've known over the years many, many people in this field, and no one is as cheerful and interesting and helpful and quite a career you had, Bruce Balick, so it's an honor to have you with us. Let's talk about your early interests and your background. You got interested in astronomy at a very early age, did you not?

*Bruce Balick:* I was five, and I remember very vividly sitting on my father's lap, and he was reading me a book — I think it was by Willy Ley — back in 1949 it must have been, 1948. It was all about the moon and the craters. Almost all of it, if I remember correctly, turned out to be wrong. That's OK. We turn out to be wrong a lot of the time, right? We believed the earth was the center of the universe for 2,000 years and let go only slowly of that incorrect idea.

Anyway, from that point on, I was just infatuated by astronomy, and you know, the usual pause to be a firefighter or things like that. I missed all that. I just went straight in, jumped into two calculus classes at the high school where I went. Fortunately, they had just marvelous teachers, and took physics both in high school, obviously in college, and it's been a wonderful ride.

I'm retired now for the past, what, eight months. Not really retired because I spend more time at my desk than I ever did, plus doing more research than I ever did.

*Dave Eicher:* I was going to say, congratulations, but then everyone I've ever known who is retired is busier when they're retired.

*Bruce Balick:* Well, you know, I — one thing about our department, you can look around, it's a young department. It's 50 years old, and only four people have ever retired, one of whom passed away last year, and the others are still cranking it out. So George Waller is fine, Paul Hodges, both in their 80s, and what phenomenal examples they are to all the rest of us. You know, their devotion — somebody probably told them to get a life, and I think that's what they did.

*[Laughter]*

I suppose that — you can go talk to a Jesuit monk or someone, you know, and the people around here — and I think the people in the field in general — have the same determination to just dig in and make a life out of astronomy. And I'm one of those, and I love it.

*Dave Eicher:* Well that's really marvelous. And that sense of dedication and a drive of discovery, that's really what has made most of the great discoveries in our field happen.

*Bruce Balick:* Well, that and incredible support. When you average over the last 50 years that, which is my career, the support for new telescopes, nationally accessible, led to the formation of many astronomy departments in the 1960s and '70s and that would include ours, right? So we had — from the time we started, we had access to national observatories, big telescopes. Telescopes that very, very few universities could ever have afforded. And we got down to work, and it's worked out extremely well. Now, of course, we have satellites flying around the Earth and space exploring all kinds of electromagnetic regions, light regions that were just — had been waiting to be plucked, and all that happened during my lifetime. It's really exciting.

*Dave Eicher:* It's a really magical time for us to be getting towards some of the answers to these big questions in astronomy and cosmology as well, but let's go back. You talked about that physics and math that you took really rapidly in high school and in college, and then you went and you got your Ph.D. from Cornell.

*Bruce Balick:* Yeah.

*Dave Eicher:* And you worked on radio studies, looking at star-forming regions, how stars form. How did you get into that as an interest?

*Bruce Balick:* I don't really know. *[laughs]* I go to graduate school, and while you think you know what you would like to specialize in as you walk in the door, it never works out that way, at least barely. And so much depends on who your mentors and who your peers are and what they're doing and how you work synergistically with all of them. So my thesis advisor was a young man at the time, maybe five years older than I am. I was his first student.

His enthusiasm was just like  a rocket engine under the shuttle. I mean you just got swept up, and so it was his enthusiasm that sent me into radio astronomy. I left Cornell not as a student, I mean I remained a student there, but I spent two years at the National Radio Astronomy Observatory [NRAO] using some of these magnificent national facilities and worked with people who were working on star formation and I just kind of fell right in.

*Dave Eicher:* And you also did — you did some work at NRAO and also at Lick as well.

*Bruce Balick:* Yes. So I was a student at Cornell, that's where my degree came from, but I was in residence at NRAO for two years and then remained for two more years as a postdoc. Those were probably my most productive years ever except now in retirement. And there came a point when I was a postdoc and reading the journals when I realized I didn't really understand much about optical astronomy. At the time, there was just radio and optical astronomy.

We hadn't yet cracked the other electromagnet spectral regions. And I realized if I was going to be successful in this field and be an astute observer, I better find out what all these other people who published most of the papers in the journals, what they were up to. So I was very lucky. I applied for a postdoc at Lick Observatory and Don Osterbrock, who was interested in having a radio astronomer come to the observatory, he had just gone there as director, and he wanted some people with the variety of different skills to interact with the staff. And I was that person and it was just magnificent.

And more or less I've remained an optical astronomer ever since. There were a few years in its infancy, when I was a major user of the Very Large Array [VLA] in New Mexico, I remember fondly working there when the — coming there as a guest when there were only four out of the 27 antennas that were working. But they were collecting data, and the director asked me to help them write software to turn the radio data into images. And I loved doing that sort of stuff. I still do it now.

And so I worked there for about six months. By the time I left, there were 10 antennas, the rest came online in a couple of years. It was a thrilling time, a really thrilling time. The VLA was unique right from the very outset.

*Dave Eicher:* Really golden age in radio astronomy. And I can remember the first time I visited there in the 1970s, being attacked by a great swarm of bees near one of the antennae, so I never got that image out of my mind, but this was really — it was a key moment in — how did — what did we understand about star formation at that time through radio astronomy compared to what we know now?

*Bruce Balick:* We understood the fundamental process 'cause it isn't that difficult. There's this soup — lumpy soup out in the interstellar medium. It's like anything that has mass. It's subject to gravitational forces. The lumps are going to condense first and go into making stars and solar systems. The spin of these lumps, which might be very slow at first, eventually speeds up as the lump condenses into a star and a disk of protoplanets forms.

I mean we didn't know that for sure at the time, that was some of the point of my research, but we sure know it now. I mean we see those disks and the planets forming within them. That was a very exciting field. But when working with Don Osterbrock at Lick, I became interested in active galactic nuclei [AGNs], which is the research he was doing. So Don would go up to the 120-inch and observe and I would tag along and help out and learn how to do optical astronomy, but also work with Don to interpret optical spectra, which I'm still doing today.

And his interest in active galactic nuclei was also infectious. We knew very little — I mean we know the essentials, but there's so many wonderful details that have been — that have emerged since then. I became interested in how the engine works, and I became frustrated because in optical astronomy, when you study these very distant, tiny, little nuclei all buried inside huge clouds of dust, you don't see much. So at the time, and it's still largely true today, our understanding of AGNs was based largely on theory. But I wanted to get closer to an engine that ejected collimated mass, that made — that ejected jets.

And my interest wandered into planetary nebulae because most of them just sit there. You can look down the snout, you can look right into the star, especially now with Hubble. You can explore the regions right around the jet engine. And we still don't see the engine, but we can very clearly identify how the engine works by its impact on the gas and dust around it. And I'm still working on that now.

*Dave Eicher:* It's interesting, you mentioned planetaries and the jet process, and you — a couple of point — I mean you came into studying AGNs with Don at a time when we — for something that — black holes had been hypothesized more than a couple of centuries earlier. We were just starting to get the evidence for the real existence of supermassive black holes.

*Bruce Balick:* Let me remind you that that path is a really crooked one that you could fall off of, right? So the idea of black holes had been hypothesized too many years before we were capable of observing anything like that.

*Dave Eicher:* Yes.

*Bruce Balick:* And we almost forgot about them, and it's only when we began getting observations that were too strange to explain in any other way that the idea reappeared.

*Dave Eicher:* And then you also mentioned — it's interesting how all these things thematically in a sense tie together, planetary nebulae and their fast jets that some of them have, there's something — a completely different process on a completely different scale, but also you're looking at the interaction of jets with material outside those jets.

*Bruce Balick:* So I don't think the process is all that different. Certainly the energy scale is way different.

*Dave Eicher:* Yeah.

*Bruce Balick:* And black holes — the outflows — are ultimately powered by the by the gravity of the infall, right? The stuff falls in, the black hole organizes that material, any magnetic fields that are needed to collimate the materials somehow get added from the spitting disk of the black hole and out squirts these fantastic jets, which for the most part can only be seen at radio wavelengths. Not entirely, but the bulk of them are best studied there. And I enjoyed that phase of my career enormously. The planetary nebulae are not powered by the infall of material; they're powered by some sort of an excretion process that takes place late in the star's life.

The name of the game in my field is to figure out what this engine is because there's nothing in stellar evolution theory to predict it. It's really weird. We can, with ever increasing confidence, track the life history of stars. We have loads of great data, more coming from the Gaia satellite. We have wonderful theories of stellar structure and evolution, and they work until the end, and then they don't work.

So somewhere right in the final death throes, the stars at the centers of planetary nebulae just blast it all out and we don't know what the power source is. I mean we can speculate, and there's lots of that, but that speculation isn't knowledge. And I've been working on Hubble images of very, very young outflows mapped with their — you know, and designated at the highest resolution that we can get from the space, at least at the moment.

And in my dotage, in my old age here, I'm learning how to run astrophysical models, hydrodynamic of outflows, and for the past week, I must say I've been developing a — this is going to sound boastful and I certainly don't mean it that way. It took me two or three years to get to where I am. It was a slow crawl. But something happened a few weeks ago, and the models that I'm running are beginning to fit these wonderful, wonderful images. You've all seen them. And —

*Dave Eicher:* And of course you made those images very, very famous. And we'll get into talking more about the different kinds, the different shapes, the morphologies of planetaries, but —

*Bruce Balick:* Yeah, but let me mention you don't get time on Hubble to make pretty pictures. They're a wonderful byproduct. You get time on Hubble to do science and it's the — it's quite clear that the symmetries, the fantastic symmetries, that we've seen in the Hubble images are strong clues to how the system works, at least not how it works down close to the nucleus that we can't observe, but we can see what it does to the material on the outside. And understanding what actually goes on takes more than those pictures. It takes a model, a good physical model, in which you put in certain conditions at the beginning of the model and outcomes a result that matches the observations. That's the path to success.

*Dave Eicher:* And so this is really a special time recently you've had here with — is it safe to say a bit of a breakthrough of looking at the modeling that you're doing now?

*Bruce Balick:* Well, I'll tell you in a month.

*Dave Eicher:* OK. *[laughs]* Sounds good.

*Bruce Balick:* You know, in this field, if you're not self-critical, you're just waiting for a disaster, so I don't want to jump too quickly.

*Dave Eicher:* Sure, sure. Well before we get into the — some real nitty-gritty details of planetaries, you arrived at the — let's follow your career path a little bit more. You arrived at the University of Washington in 1975. You've been there ever since.

*Bruce Balick:* Yep.

*Dave Eicher:* You've served as chairman of the department, and you've also taken leaves to go and work at a number of other places. You mentioned the VLA, you've gone to Berkeley, you've made a bit of a second home, I understand, in Leiden as well.

*Bruce Balick:* Absolutely. Leiden is my home away from home. I love the people there, I love the city, it's just so nice to be able to fly into Amsterdam on our way to somewhere in Europe and spend a day or two with friends on the way in and the way out.

*Dave Eicher:* And you've had — so you've had both professional and personal, that's a great place in your heart.

*Bruce Balick:* But, you know, the astronomical community is full of potential friends.

*Dave Eicher:* Yes.

*Bruce Balick:* And you just show up and you start making them. It's not a challenge.

*Dave Eicher:* And that's really funny because there is some fields where everyone sort of feels naturally like a competitor, and astronomy is, as you just said, the exact opposite of that. And it's —

*Bruce Balick:* Well we have had our moments, Dave.

*Dave Eicher:* *[Laughs]* OK.

*Bruce Balick:* But I think we all realize that when we work together to realize really ambitious goals, we're going to get — if we do this well, we're going to get satellites and telescopes on the ground. That's our feed corn. We need those things. And I at least feel that, OK, if I'm not lucky, if the next instrument is going to do any good for me, you know, the one after that or maybe the one after that will line up with my interests. And I think we've become used to that.

You don't win them all, but, you know, new instruments have this wonderful habit of revealing all kinds of surprises. I love this story. So before Hubble released its first image of a planetary nebula, there was a conference that I had attended along with my student at the time, Adam Frank, now at Rochester, and several other people from Leiden. It was a talk on the theory of the structure of planetary nebulae. They — from the ground, you could tell that they had these wonderful symmetries.

The question was how do we read the hints? How do we read the tea leaves to figure out how they work? And so there were several papers given, one by my student who I think compellingly convinced the audience that we were on the threshold of doing hydrodynamic studies. It would solve all the problems. And so we went out for coffee that afternoon, the group of us, and said, OK, time to find another field. Well, *[laughs]* wouldn't you know it, the next day the first image of a planetary nebula from Hubble was released.

*Dave Eicher:* Wow.

*Bruce Balick:* And we saw it, and we took one look at it, and there were too many devils lurking in all of those details. We knew that we were guilty of the sin of — what's the opposite of humility? *[laughs]*

*Dave Eicher:* Very nice, very nice. You've also spent time at Arcetri near Florence as well, where other famous astronomers were known to have hung out at one time.

*Bruce Balick:* You know, you don't get any closer to heaven then Arcetri. Arcetri is the hill on the south side of Florence.

*Dave Eicher:* Yes.

*Bruce Balick:* And I lived in downtown Florence and would bike up my way — I would bike up to work every day up this big hill.

*Dave Eicher:* Wow.

*Bruce Balick:* On the way, I would pass the homes of, oh, you name it. You — you know, all these people that changed the course of human history in the 14th and 15th century.

*Dave Eicher:* Yes.

*Bruce Balick:* So I get up early, and I'm riding these streets, and there's no traffic, and you look around and you say, "I can imagine what it was like here 500 years ago. What an honor to be here." And so you work your way up the hill. By the time you get to the observatory, you're looking down on this beautiful, beautiful city. I was there in the spring, and the city is especially nice when the flowers are out. And I had an office that had just one window in it, and it was way up above my head, so I couldn't look down on the city of Florence and enjoy its beauty. In fact, the window even faced the house where Galileo had been placed under house arrest.

*Dave Eicher:* Imprisoned, yes.

*Bruce Balick:* That, not going outside. And I remember going into the director's office and asking for a TV camera to hook up to the window so I could see all the — it's an — I mean, you know, the people are so nice, the food is just wonderful, the museum exhibits, especially in the winter when we were there, they were empty and you could wander in and just explore on your own.

*Dave Eicher:* So you were a frequent visitor to the —

*Bruce Balick:* I'll never forget that part of our — in fact, my wife and I go back to Italy now regularly to a place down south of Florence that I won't reveal because we don't want it spoiled.

*Dave Eicher:* No, of course not.

*Bruce Balick:* We've seen what Rick Steves has done to the —

*Dave Eicher:* Right. *[laughs]*

*Bruce Balick:* — Cinque Terre, and we're not going to let it happen to this place.

*Dave Eicher:* Right.

*Bruce Balick:* Anyway, these travels abroad are phenomenally productive from a scientific point of view, and you learn so much about the world and the way it works and it's just marvelous. And we dragged our kids along with us everywhere we went. They were at the age where they didn't want to go, but by the time we came home, they were buying plane tickets to go back and stay with their friends.

*Dave Eicher:* And you can really feel that magic. You can feel the sense of commonality of the molecules of Galileo still being — lurking around. And —

*Bruce Balick:* Oh, yeah.

*Dave Eicher:* — the convent, you know, where Galileo's daughter was, you know, down the road —

*Bruce Balick:* That was just down the road from Arcetri.

*Dave Eicher:* — and the olive trees around on the hillside and then the Uffizi Gallery, you know, doesn't hurt it either. It's really a magical place, isn't it?

*Bruce Balick:* It is. And what happened during those times was the reinvention of art and architecture, and then thanks to Copernicus and Galileo and others — Kepler — science was reinvented. Science — you know, the Greeks did a great job of doing science, but by the time the Dark Ages came along, we had forgotten how to explore. We had forgotten that evidence has to be the basis of belief. And so humanity went off on this — outside the Muslim world at least — humanity went off on this tangent. And it took Galileo, who paid dearly for his efforts, to put the train back on the tracks. And it still is. And to be there, especially when it's quiet and the Sun is just beginning to come up and you can let your imagination run absolutely wild, it's fantastic.

*Dave Eicher:* Very inspiring, and you get the feeling that anything is possible sort of being in that aura a little bit, and you know, as I understand, I mean I think it's true that Galileo had heard and panicked intellectually that this telescope device was even for sale on the streets of Paris. Very simple, low-power telescope, something that he had always dreamed of inventing. And so he raced back to Padua and from that which he had heard, put his device together so that he could go straight to the doge and not lose —

*Bruce Balick:* He was no fool.

*Dave Eicher:* *[Laughs]* Yeah. I mean you can't —

*Bruce Balick:* He figured out — he understood the principles of the telescope as soon as he heard about two lenses.

*Dave Eicher:* Yes.

*Bruce Balick:* And he employed — don't ask me for the details of the history, but I understand that he employed a glassmaker. So when it was time to make a few lenses, Galileo was ready to go and the telescope was ready the next morning.

*Dave Eicher:* Yeah. I mean it really — you cannot — if you wrote this into a Hollywood script, it would be unbelievable.

*Bruce Balick:* Yep.

*Dave Eicher:* Yeah.

*Bruce Balick:* And that, you know, now it takes us 50 years to get a telescope up into space, and he made the first one in an evening. *[laughs]*

*Dave Eicher:* It's really, really incredible. Head spinning. You've also worked — well you've worked a lot and largely with planetaries, but perhaps some other things as well with Hubble. What was the experience working with the Hubble Space Telescope? What has that been like for you?

*Bruce Balick:* Well it's been a thrill, but it's a lot of hard work, right? So scientific proposals role in but there's not enough time on Hubble to schedule more than about an eighth of them. So writing proposals is a bit of a crapshoot. You put a lot of work into it because if your proposal isn't great, you're not going to get any time. But you get used to rejection.

It does happen. Anyway, when you do score, at least in my case and for most of the observations, you don't know when the observations are going to be scheduled. They're scheduled when the Sun is right and the telescope is right and it happens to be in the right place at the sky, whatever. And then you get an email, *boing*. You have new data in the archives.

Those are your observations. You don't go anywhere. You're not looking through a telescope. It's just silence until the time you learn that your images are already on the ground and in the database. So it's with great excitement that you log in and you download your images and you put them in Photoshop or you find a way to begin to look at them.

There's this period of absolute elation when you look at these things because they're so much better and often so much more surprising than anything you would have imagined. And that ecstasy lasts five minutes or so, and then you realize, wait a second, I got these pictures in order to explain what they reveal, right? That's hard work. So, yes, there's elation. I mean being the first to see some of these incredible images that I've take — other people have the same sort of an experience — it's wonderful. It's just wonderful. You're body just goes wild with endorphins, or whatever they're called, and it takes about two or three days to come back down to the planet. But you land with a thud, right? *You* have to figure out what's going on.

*Dave Eicher:* It really raises the old — the joke about research, where someone says I'm going to go down to the library and research my paper. And that's not what research really means. *[laughs]* Research is what you're doing — you're finding out things that nobody knows yet.

*Bruce Balick:* Yep.

*Dave Eicher:* Probably from that, and it's a little bit more difficult than pulling books off of a shelf.

*Bruce Balick:* Well, you know, it's not quite that simple. Often you get time on telescopes to test theories. So you'll — surprises come when the theory turns out to be incorrect, and that's an important step forward. But I think a good bit of the time you're verifying — not proving, there's a difference — but you're verifying that theories are viable. You can't prove anything in science. I mean that's the biggest mistake out there among my students in astronomy 101 where they talk about scientific proof as if it really exists. Forget it.

*Dave Eicher:* It's the slow —

*Bruce Balick:* Always new data around and just wait long enough and any theory falls. It'll happen to relativity. It happened to Newton. And it'll be exciting when it happens.

*Dave Eicher:* What we're hoping for is the slow refinement here, and those eureka moments of clarity are not necessarily going to have — science is a slow, huge, gradual process.

*Bruce Balick:* Well that's because it has to be self-corrected, and that — when I mentioned earlier, I need a month for self-criticism, I meant it. That's a key part of science.

*Dave Eicher:* Let's talk a little bit more about some of the areas of research that you've done now. Have you been doing AGN research recently? Is that something that —

*Bruce Balick:* No. I've been following it, but I haven't been engaged.

*Dave Eicher:* Yeah. And how about — you've also in the past neutral hydrogen in ellipticals and lenticulars and in galaxies. What do you — tell the listeners, if you would, about neutral hydrogen and what you derive from that? What do you learn about —

*Bruce Balick:* And that's ancient history, David. *[laughs]* So neutral hydrogen, among many other things, is a tracer of structure in the universe because it's so ubiquitous. If you can figure out where it is and how fast it's going, you're — think of it as being on the desert, and there's a dust devil. Now really, there's an air devil, but air is transparent, and you can't see it, so without the dust, you can't tell that it's there, right? Neutral hydrogen is roughly the same way.

It's the tracer that tells you where stuff is and how fast it's going, and it's vitally important for structures, especially large-scale structures like the Milky Way that are just loaded and loaded with all kinds of neutral hydrogen. Now planetaries don't have any. They ionize it all or they form molecules out of hydrogen. So atomic hydrogen studies of planetaries are not particularly productive.

But back in those days, I was I would dallying in galactic structure, for the most part trying to understand how a supernova does damage to the medium that pervades the Milky Way. So obviously there's a hell of a lot of damage in the first few years, but these studies were, all right, so what happens after 10,000 years? Is the supernova stirring up the gas, or has its impact been just ignored and forgotten? Do other things dominate the impact of a supernova event?

*Dave Eicher:* Were you looking at that for — with an eye toward gas compression and star formation later on or —

*Bruce Balick:* No, I don't think I did that.

*Dave Eicher:* OK, the event itself and how it affected the medium around it.

*Bruce Balick:* Yeah. And these days, when I'm not working on the models of planetaries, I have a delightful collaboration with people around the world working on observational studies of the origin of carbon. You know, where does this carbon stuff come from? It was not there when the universe began.

Had any been able to form, the heat and the collisions that come with the heat would have destroyed it, and so two or three minutes after the Big Bang when matter really began to cool and hydrogen and helium had formed, there wasn't any carbon. I mean there might have been on atom some place, but really, all the carbon that we're used to now came from stars. That's where today conditions are dense and hot enough that you can get nuclei of hydrogen and helium to react with one another and follow the path to making carbon. That's not an easy path, but let's not worry about that for now.

Now the main producers of carbon are planetary nebulae and other very old stars, that is these stars are born with some measure of carbon left from previous generations for sure, but they shine, the stars shine, they derive their energy from nucleosynthesis, and during their lives they produce a fair amount of carbon out of helium that they were born with or made later. And we only have a poor grasp of the mechanisms and the rates at which carbon in the universe are being enriched. So we look at planetaries because the fresh carbon is coming out in the gas that they eject.

So I'm not the only one working on this. I'm kind of a — our team is doing some great work, but I'm just part of that team, I'm — a lot of the ideas come from my wonderful colleagues. But we have been trying to use planetaries in the Milky Way to trace the production rate of carbon. The problem with the Milky Way is you can't see much. Most of the planetaries are hiding behind the dust clouds. And technology has now reached the point for the first time where we can do a really good job of measuring carbon abundances in planetaries in the Andromeda Galaxy.

We know the distance to the Andromeda Galaxy, unlike the distances to local planetaries, and that tells us their luminosity. From that, we can derive their masses, we can see where they're located in the Andromeda Galaxy, and are they where they should be given the history of star formation that we understand from very deep stellar studies? In the inner part of M31, the Andromeda Galaxy, the planetary nebulae there, for the most parts, seem to be where they should be, that is where there're plenty of old stars. We realize, though, that there — in a survey not done by us but by others — there were many, many, many, too many planetaries way beyond the disk of M31.

Far out there in what you might think of as the halo where there aren't any stars left that can produce large amounts of — large numbers of planetaries, and yet, there they were. The Milky Way doesn't have them. Our halo is almost devoid of planetaries. OK, you can argue that we'll discover more, and we certainly will, but we're already seeing lots of them in M31, and it's farther away and these planetaries are quite faint. And much to our surprise, after we did the spectroscopic observations, we're finding that these planetaries — and beyond the disks, the disk ends where the spiral arms peter out. We're talking about distances, which are five, six, seven times larger in distance than the outer edge of the disk.

*Dave Eicher:* You're kidding!

*Bruce Balick:* And there are planetaries, and one after another they turn out to have almost solar abundances of carbon. Stars near them have the element abundances that are just a tiny fraction of solar, less than a tenth. And here these planetaries form a population that are just dripping in oxygen. We can't see carbon at those distances. The signature of carbon's just too faint to observe. But we use oxygen as a proxy, and these things have — these planetaries are really rich in oxygen. And of course this is an interesting story, which at the moment is largely speculation. We talk — we speculate that M31's large companion galaxy, M33, what's it's popular name? I can't remember.

*Dave Eicher:* Well, the Pinwheel or the Triangulum Galaxy.

*Bruce Balick:* The Triangulum. We hypothesized that thing wheeled on past M31, not through M31, but around its outer edge about 3 billion years ago. Three billion years is the age of these planetaries that are rich in oxygen. So you surmise that that interaction of M33 with M31 left the — that is, young stars which are now planetaries and which have lots of oxygen and probably carbon.

*Dave Eicher:* Wow, that's amazing.

*Bruce Balick:* The abundance — the ratio of these two things is pretty constant.

*Dave Eicher:* Yeah.

*Bruce Balick:* And figuring out how that worked is — you know, it's one thing to say, oh yeah, M33 must have done it. No, that's just dreaming, right? That's waving hands. How did it do it? And that's the challenge before this group that I'm working with right now.

*Dave Eicher:* Boy, that's an amazing story. That's really incredible. And of course, those two galaxies so well known and loved by amateurs, by observers.

*Bruce Balick:* Sure. And M31 is headed our way in another 4 or 5 billion years, so —

*Dave Eicher:* Yes, indeed. And eventually becomes Milkomeda and we can thank Avi Loeb for that, huh?

*Bruce Balick:* Yeah, exactly.

*Dave Eicher:* Yeah. *[laughs]*

*Bruce Balick:* I just hope somebody will be here to see it.

*Dave Eicher:* Yeah, yeah.

*Bruce Balick:* The rate at which we're going. *[laughs]*

*Dave Eicher:* Yes, indeed. And I hope it's an interesting collision because then, you know, way on down the road the entire universe will eventually only observationally exist of what's left of Milkomeda.

*Bruce Balick:* Exactly. So this winter I taught a course to first-year students, it's a 100-level course, so it's undergraduates, that I've long wanted to teach. And the name of the course was Cosmologies and Cultures. And I wanted the class ultimately to explore the Big Bang theory, which is the backbone of an astronomy course like the one I gave, to stories of creation that come from the American first peoples, from ancient Egypt, from China, from India.

So let me try to get back on track here. *[laughs]* Let's let the details of the course slip aside. What I had to do was to learn Big Bang cosmology in a manner that could be explained to first-year students who typically aren't really good at Romanian geometry, right? You have to get the story out there, and you have to be able to weave all the recent and exciting observations that constrained the physical theory. You have to weave those into the story of what we learned and how we learned it.

*Dave Eicher:* Yeah.

*Bruce Balick:* I love teaching that.

*Dave Eicher:* Yeah.

*Bruce Balick:* And I learned so much more about cosmology. You know, as anybody on the faculty can tell you, you don't really know a course until you try to teach it.

*Dave Eicher:* *[Laughs]* Yeah, right.

*Bruce Balick:* So, I was going get back to M31 and M33 here. Oh, oh. You know, I'm *[laughs]* — I've reached the age *[laughs]* the powers of concentration —

*Dave Eicher:* Well you were talking about the — we were talking about the limits in the observable universe many trillions of years from now on the horizon and so on. I don't know if you were going to talk about that.

*Bruce Balick:* Yes. So I did learn what we — not me, others — think the universe holds in store. And it's not a really exciting picture. This dark energy discovered not long ago, 20 years ago or less, is going to cause the universe to expand and expand and expand. As it does so, the density of galaxies and the density of — yeah, the density of galaxies is going to do down and the universe is going to become lonelier and lonelier and lonelier, and colder, and eventually, since we won't be able to interact with other galaxies and find new sources of gas for a star formation, the stars that are here are going to burn out and they're not going to be replaced.

Now we have a few more generations of stars that we can form, but it's already the case that the massive stars today form at a far slower rate than they did five billion years ago. We can see that. And that's the direction for the future. So star formation is going to slowly stop — grind to a halt. We're going to use up all the remaining reserves of stuff from which stars are made, gas and dust, and the universe is going to — I mean the galaxy is going to turn into endless numbers of white dwarfs that go black and a few black holes and some other miscellaneous things.

And over the course of time, and here we're talking about ten to the one-hundredth years, quantum mechanics is going to lean to the evaporation of the matter from within these things. And so in ten to the hundredth years, come back then — you probably won't be able to. But if you could, the universe would have lost its beauty and its form. The stuff we see in the sky now will be ancient history, right? The universe will just be a soup of tired old photons, really low-energy photons, thanks to the expansion of the universe, and a sea of protons and some electrons and probably lots of neutrinos with nowhere to go and nothing to do. No opportunity to recollect and form new generations of stars.

*Dave Eicher:* It's a very —

*Bruce Balick:* But that's gloomy, and astronomy is much more fun than that is, so let's go back to —

*Dave Eicher:* *[Laughs]*

*Bruce Balick:* — to the present. We live in a golden age, right? We live in an age where there's lots of stuff from which to make life. It wasn't true at first, and it ain't going to be true forever. We live in the right part of the Milky Way for this to happen. If you go in closer to the center of the Milky Way, supernova explosions are probably going to sterilize planets long before sophisticated life develops. If you go to the outer edges of galaxies, the content of the heavy elements, like carbon, that are essential ingredient for life — not much of them out there. So we're in the sweet spot right now and here. And of course, the same would be true in similar galaxies as well. So it's a great time to be alive. In fact, it's probably the only time to be alive.

*Dave Eicher:* *[Laughs]* It's a great time —

*Bruce Balick:* When you look out and you see the universe that is so stunningly beautiful, so incredible. You know, go look at the ancient galaxies that Hubble sees out there at 13 billion light-years. They're a bloody mess. They're not pretty. They will be, give them enough time. Things will settle down, structure will form. And we're kind of there — we're here now that that structure has formed. It's fun to look back at our ancient history, thanks to Hubble and other instruments like it. We can get a better view of our own cosmic history than historians can get of, you know, the Sumerian culture, which is an amazing thing when you think about it. And it's there to be enjoyed.

*Dave Eicher:* It's really an incredible time and an incredible place for us to be, as you so eloquently said, and we don't have to think too much about that anticlimactic ending because the —

*Bruce Balick:* That's right.

*Dave Eicher:* — beginning of the cosmic movie was a little more exciting.

*Bruce Balick:* But just go back 500 years when the question of how did we get here was a question that was owned by the philosophers. There was not a really any — not even a smidgen of evidence to support stories. You could make up — and people did — so many stories of star formation and planet formation. We live in an era where we can test all these ideas, that we can sort the good ideas from the bad ones. What an incredible time.

*Dave Eicher:* It's quite remarkable. It's a very magic time. And speaking of which, you have been at the center of a revolution in finding out some of how this universe works and the details, and I know because for a while there I called you every three or four years to talk about it. And you schooled me well in your work, deciphering how planetaries form and the — you've been really at the center of figuring out the different shapes of planetary nebulae.

*Bruce Balick:* I'd say that I've done my share, but it takes a village.

*Dave Eicher:* Yes, it takes a village, but you've been a very important central character in that story. But that's been a big part of your research and your life.

*Bruce Balick:* Yes.

*Dave Eicher:* So let's talk about — we go back a generation and we didn't understand why planetaries, stars that have similar mass to the Sun, at the ends of their lives, why they had different shapes and how they formed. And you were really central with your research associates, Adam and many others, in figuring this out. So let's talk, if we could, about —

*Bruce Balick:* No, no, no, no, no, no. I didn't figure it out. I presented pictures, which serve as hints for figure it out.

*Dave Eicher:* OK.

*Bruce Balick:* We still haven't figured it out.

*Dave Eicher:* OK. But we didn't know —

*[Crosstalk]*

Oh, I'm sorry.

*Bruce Balick:* I mean there're all sorts of bad ideas that have fallen by the wayside.

*Dave Eicher:* Sure, sure.

*Bruce Balick:* Very popular ideas when I was a kid, and they're gone.

*Dave Eicher:* Sure.

*Bruce Balick:* But we still haven't crossed the finish line.

*Dave Eicher:* No, we don't understand it fully, but if we go back —

*Bruce Balick:* Depends on what it is.

*Dave Eicher:* If we go back 25 years, we really didn't know at all what the story was, the details of the story.

*Bruce Balick:* That's right. And so we're working our way forward by throwing bad ideas to the side. But we're still — I mean we have all kinds of beautiful stories to tell about how it might happen, but it will take a combination of more detailed observations and, you know, with JWST, the James Webb telescope coming, you can see how this might happen. Even more important, I think, will be the large radio telescope in Chile, ALMA. That's really, really beginning to become productive.

*Dave Eicher:* Yeah.

*Bruce Balick:* And all kinds of wonderful data that will constrain our ideas and help us to separate the wheat from the chaff. That's on the way. So this field is going to be fun for a long time to come. But throwing out bad ideas is a little bit different than finding the idea that works.

*Dave Eicher:* *[laughs]* Well, for the listeners who don't know, if you would, in a general sense, walk them through what happens to a star like the Sun as it approaches the end of its life and how does it produce one of these beautiful cocoons that the observers, the amateur observers, are familiar with looking at the Dumbbell Nebula, the Ring Nebula, and so on and so forth. How does that process generally work?

*Bruce Balick:* All right. Let me focus on what we do know because the ultimate answer to your question is not yet known.

*Dave Eicher:* Yes.

*Bruce Balick:* So let's walk halfway down the path.

*Dave Eicher:* Sure.

*Bruce Balick:* A star like the Sun is, relatively speaking, a fairly simple animal, that is we fully understand — or we think we do — how it generates its heat down in its core. That's the inner 10 percent of the structure of the star where the outer layers of the Sun, or a star, crush down on the core, and the core gets hot, really hot, and dense, extremely dense — well, not a whole lot, maybe 100 times denser than water, but that's a whole lot denser than the outer parts of the star. I mean Earth's atmosphere is much denser than they are — the outer parts of the Sun.

This squeeze, which generates heat, triggers ultimately nuclear reactions in which hydrogen combines in a series of reactions to produce helium, and the mass of the helium that's produced in these reactions is just an itsy bitsy amount smaller than the mass of the hydrogen atoms that you begin with. So $E=mc^2$ now I'l use. The change in the mass between helium and the initial hydrogen comes out in the form of energy, and that's the energy that makes the Sun shine and sustains life on Earth. And we can see how much energy's coming out just by looking up at the Sun.

We can't see into the center, but I think our physics is so good and our ability to predict stellar evolution is so fantastic that we really do understand what goes on down deep inside. So if you follow that path through the physics, you learn that in 5 billion years, the core of our Sun will be running out of hydrogen to turn into helium. And most entry-level students in my astronomy class would say, "OK, that's the end. Bye-bye."

The Sun will fade, its residual heat will disappear, and no more Sun, no more star. No. At that point, the Sun begins to get more luminous as well as bigger than it did during the entire phase when it could burn hydrogen. Why? Well that core didn't go to sleep.

That core is still being crushed by the weight of the outer layers of the star, and its temperature goes up from 10 million or 15 million degrees needed to burn hydrogen into helium and is headed up, up, up, up, up, up, up. It doesn't take long until that squished core —

containing mostly helium, the ashes of the hydrogen burning — the helium reaches a temperature of 100 million degrees. The density is off the charts now. So these helium nuclei are smashing into one another all the time and with great energies, and they can make carbon. I'm skipping a few steps here, but the essence is, helium — you get a second pressing, right?

Helium will burn to make carbon, and the rate at which helium burns is phenomenal, much more than the rate at which hydrogen produced energy. That is, the helium-burning phase produces energy at roughly 1,000 times the rate that the Sun produces it now. That can't last. That just can't last. And for our Sun and stars of comparable mass, that is kind of the end of the story for the nucleus.

It's now a carbon ball on its way to becoming a white dwarf, which is a carbon star. And at this point, the story of what happens is fairly well understood for a while, and then strange stuff happens. But basically, the carbon core becomes extinct. The hydrogen and helium that surround it can burn for a little while longer. There's still fresh fuel and the weight of the outer layers of the star can ignite nuclear reactions in them, but that too is going to go away, right?

And it's just about at that time when the fuel runs out that you get a planetary nebula, that is the star decides to eject roughly half of its remaining mass, at least the star like the sun. Half of its mass. More massive stars eject even a larger fraction of their mass. And out it comes in a big stellar sneeze forming a planetary nebula. We don't know how that works.

We don't know how that works. So these beautiful planetary nebulae formed within the last few thousand years — I mean you can tell that from the rate at which they're getting bigger. What happened? We know roughly what the luminosity and the temperature of the star is at the time the planetary is ejected, but we're not understanding completely the formation of the vast bulk of planetary nebulae.

If planetaries were nice and round, you could just say, well, the star throbs or something and coughs and sputters, and it shakes material off of its round surface, and it would make round bubbles of ejected gas every time it quivers. Well, fewer than 10 percent of planetary nebulae are round. Most of them are squished round, that is they have an elliptical shape. And we ought to be able to understand something that simple, but we don't, right? We don't know where that elliptical shape comes from, and then a lot of them are these beautiful things like the Saturn Nebula and Minkowski's Butterfly, and you name it.

And we really don't know what happens there. Now, there are ideas. Stars have magnetic fields, and magnetic fields, even those in the Sun, guide the solar wind because charged particles are trapped on magnetic field lines, and now the winds will go where the field lines take them, and that might be something fairly interesting. We have never demonstrated directly that stars like planetaries have magnetic fields that are guiding their winds, but if the winds are there, you can make some of the structures that we see.

That's a long way from establishing that magnetic fields are there. We're just saying, could be, could be. And that's one idea that is being actively pursued in research as the tools, especially the ray in Chile, become capable of measuring magnetic fields. Another idea, which is far more popular but no better established, is that many stars have a binary companion star.

Now often the binary companion star is so far away from the, you know, like way beyond Jupiter, so far away from the aging star that we've been talking about that it can't have any influence. But in some cases, the companion star might be closer to this aging star at the time when that aging star swells way up, after the helium-burning phase happens. And if so, then that companion star and its gravity are like a little eggbeater in an orbit around the star that's going to eject its outer layers, and that eggbeater can have an effect. It can throw off a disk or it might — I mean it might — there are all kinds of ways in which the companion star might influence the winds from the dying — the bigger dying star.

And Adam Frank, my colleague at Rochester, and other people are looking at hydrodynamic models of close binary systems where one star is producing a wind to find out what influence the companion star has. And they're just really getting started along those lines of research, but what's exciting is that they have the right tools to do this job well. And the early indications are that that could — that path, that idea of the close binary system is likely to be a lucrative explanation, a productive explanation, for what goes on. Little too early to tell, but I, who was — has been a skeptic — I am, ask my wife. *[laughs]* I need more evidence before falling for an idea like that, and even I am coming around. I think this is going to get really interesting in the next five or 10 years. And I'm going to be in there playing in that sandbox.

*Dave Eicher:* This is not a time to leave retirement or not; this field is really getting even more interesting.

*Bruce Balick:* There's never a time.

*Dave Eicher:* Yeah.

*Bruce Balick:* There's never a time to leave.

*Dave Eicher:* Yeah.

*Bruce Balick:* So, you know, death is the best thing for young astronomers because without some of us getting out of their way, they're not going to get jobs.

*Dave Eicher:* *[Laughs]*

*Bruce Balick:* You remember — you heard this before — the best thing that ever happened to humanity was the asteroid that wiped out the dinosaurs.

*Dave Eicher:* Right? Yeah, yeah.

*Bruce Balick:* Right. So that's the kind of story I'm telling here.

*Dave Eicher:* *[Laughs]* But it's interesting because there're so many shapes of planetaries, and we know that some of the stuff that comes off of the star throughout the whole planetary nebula formation process comes off at a whole range of velocities too, and so the interaction —

*Bruce Balick:* Velocities and patterns.

*Dave Eicher:* Yeah.

*Bruce Balick:* I spent three or four years just gathering pictures of planetaries, especially the young ones, and staring at them and trying to realize some sort of a story that would tie all these different structures and the ejection speeds together. The ejection speeds are typically — well, 20 is slow. 200 miles per second is not unusual, and a few get up to 500 miles per second or even more.

*Dave Eicher:* Wow.

*Bruce Balick:* That's one of the problems with the magnetic field model. It's very hard for particles — lots and lots of them, like half the Sun's mass — to be accelerated up to these speeds just by putting them on a magnetic field. It doesn't work. The binary, the close binary system, where one star serves as an eggbeater for the other, for the mass being lost by the other, that can provide energy and momentum and speed. We still haven't understood exactly how that works, but at least we can imagine the source of energy momentum and, you know, mass and things like that in the binary star hypothesis.

*Dave Eicher:* Interesting. Where do you see the study of planetaries — you mentioned, five, 10 years from now — do you think this process will be much better understood a decade from now?

*Bruce Balick:* No, no. No, go back — well, it's now 20 years, and look at the chaos that Hubble unleashed on this community, and don't imagine for a moment that it's not going to happen again. So where are we going to be in 10 or 20 years? I predict we're going to be surprised. But it's through these surprises that we make a lot of headway.

I mean at least you get a chance to throw the bad ideas out and focus on the ones that are good. Now science churns. Look what Hubble has done to one field after another after another after — made us go back to the drawing board and think harder with some information to guide us, of course. And we're in the era of an explosion of knowledge, and it's not just Hubble, although certainly that has played a central role.

It's all the other new facilities, the X-ray telescopes, the infrared telescopes, new radio telescopes like the one in Chile, the one in New Mexico. It's this rich array of ways of extending human sensory and perception that keep the field moving forward. I love it.

*Dave Eicher:* Fantastic. What an exciting note to end on because I'm afraid that we are out of time. But thank you so much, Bruce Balick, for joining me today. I hope you enjoyed this as much as I did.

*Bruce Balick:* My pleasure. It's always fun to talk about these things.

*Dave Eicher:* Thanks so much. I'm sure the listeners will enjoy it, and we will see Bruce Balick and his work I'm sure many times again in Astronomy magazine in the months to come.