NEIL DEGRASSE TYSON

science's endless golden age

N o doubt about it. We live today in the golden age of cosmic discovery. With missions to Mars, Jupiter, and Saturn, and striking images arriving daily from the Hubble and other telescopes, we enjoy weekly reminders of our place in the universe. Remarkably, this golden age applies not just to our understanding of the universe but to nearly all scientific discovery.

To quantify this golden-age claim in astrophysics, I performed a simple experiment. I spend some part of each week in the department of astrophysics at Princeton University, whose library subscribes to twin copies of the *Astrophysical Journal*—one circulating and one not. Along one uninterrupted stretch of the library walls is every single issue ever published of this journal, which goes back to 1895 (about when the word *astrophysics* was coined—born in the marriage of the analysis of laboratory spectra with the analysis of stellar spectra). One day while browsing the journals I asked myself, "What year corresponds to the geometric middle of this wall?" When I did this experiment, the middle landed in 1986, which

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means as much has been published in astrophysics in the past 15 years as was published in all the years before that. Extraordinary it was. But how extraordinary?

I decided to check other journals as well as books. The fact is yes, in all media as much has been researched and published in the past 15 years as has been published before then—a 15-year doubling time. Astrophysics has been largely computer based since the late seventies, about when we started taking digital data with CCDs at the end of our telescopes rather than with photographic emulsions. So, the Internet, when it finally became widespread, became the natural medium for us to share our data and our research results.

One might now ask the question, "On what level does Moore's law contribute to this doubling time?" If astrophysics doubles every 15 years and Moore's law doubles computing capability every 18 months, then there remains a large discrepancy. Whatever else it means, we can conclude that cosmic discovery is not linear with Moore's law. Indeed, the pace of cosmic discovery badly trails the pace of computing.

How justified am I when I claim that there have been twice as many discoveries since 1986 as before? Maybe people today are more verbose. Maybe people are publishing more junk now than ever before. Maybe the rules for academic tenure are forcing us to publish more papers than before. So I asked some old-timers, "In your day, what were you saying to each other about the quality of research in the journals?" For every generation of colleague I asked, they always complained about how much junk was published in their journals. So at least the junk factor hasn't changed—perhaps we've discovered a new constant of nature!

We may conclude with confidence that more science is actually happening today than ever before. There are not only more astrophysicists, there's actually more stuff going on. You would have to be living under a rock to not know and agree with this.

Now, let's consider for a moment as to how it might be that modern astrophysics can be so dependent on computing power, yet computing power has enjoyed 10 doubling times (a factor of a thousand) over the past 15 years while astrophysics has doubled only once.

The answer may be quite simple. In astrophysics, the large-scale structures of galaxies in superclusters are 40 orders of magnitude

larger than the size of an atomic nucleus. If you're going to use your computer to simulate some phenomenon in the universe, then it only becomes interesting if you change the scale of that phenomenon by at least a factor of 10. If you change it by only a factor of a few, you don't really expect to test a new realm of the cosmos. Let's attempt to model the 100,000 stars in a cluster, where all stars accelerate according to the sum of all gravitational forces from every other star at every instant. This scenario poses an interesting computational problem that we've been trying to tackle for the past 30 years, ever since computers were first turned to the problem. When you approximate this problem with, say, 100 particles, you double the grid size. Then you'd have 8 times the volume, but would not fully enter another astrophysically interesting domain. What you really want to do is increase the grid size by a factor of 10. For a 3-D simulation, an increase by a factor of 10 in each of three dimensions increases your volume by a factor of 1000. And that's just the beginning. You may choose to put more particles in the volume and then account for that many more gravitational interactions over a longer period of time. Or perhaps you seek finer resolution in time itself.

Isn't that interesting—Moore's law gives us 10 doublings in 15 years, just the pace needed to sustain the doubling rate of astrophysics. Yes, it seems that we need Moore's law to live on because so much of what we do depends on computational advances.

At the new Rose Center for Earth and Space in New York City, one of our exhibits uses its principal architectural element, the sphere, to convey the 40-powers-of-10 range of size scales in the universe. In Fig. 1 we see an early evening view of the Rose Center for Earth and Space in which the 90-ft diameter sphere containing the rebuilt Hayden Planetarium is in full view. The twenty-first-century planetarium does more than just project stars on a dome. We can now take you anywhere in the cosmos via a matrix of video projectors connected to mini supercomputers, as long as we have data for the objects and region of the universe where we wish to take you. We are therefore limited by our data and not our technology. Outside the sphere, as you walk around it, we have suspended orbs and mounted models along the way that take you from the large-scale structures of the universe all the way down to the atomic nucleus—it's a walking tour of the powers of 10 in the universe.
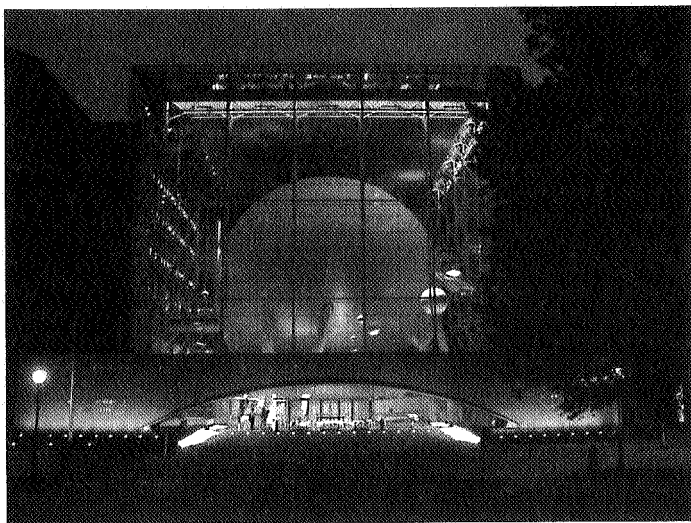
Figure 1

The walkway's most photogenic spot is where we have suspended the four Jovian, gas-rich planets Jupiter, Saturn, Uranus, and Neptune in proper relative size to the sphere of the sun. Along the railing below are small models of the four terrestrial planets Mercury, Venus, Earth, and Mars. This particular display omits Pluto, which upset all kinds of people. But that's another lecture for another time. Toward the end of the walkway, on the far right of Fig. 2, you enter the scale of molecules. The three colored balls represent the molecules water, ammonia, and methane, which are common in the universe. On that scale, the sphere represents a rhinovirus.

Where 100,000 stars orbit their common center of mass, gravity is the only force at work, which is a computationally intense yet simple, well-defined problem. It's just Newton's law of gravity at every step. For flavor, you might throw in a stellar evolution code, allowing stars to be born, live out their lives, and die, some explosively. While all this represents important activity in the life of the cluster, from the point of view of the algorithms, you basically carry this information along for the ride. Fig. 3 is a Hubble Space Tele-
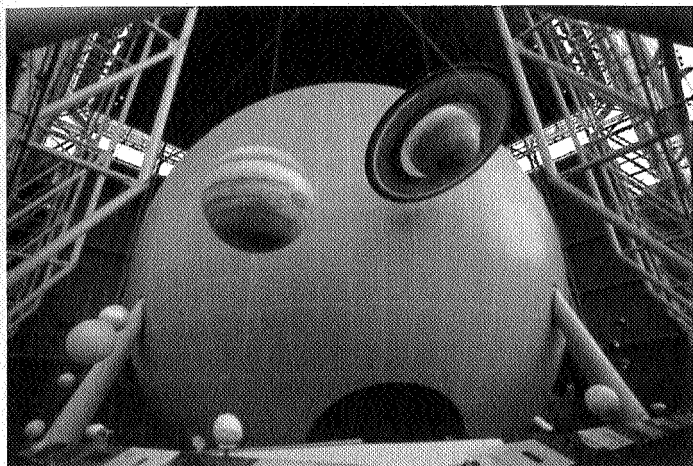
Figure 2

scope image of M80, a well-known cluster of stars that has yielded to computer simulations of its long-term behavior. In an astrophysical milestone, reached at year's end 2000, we can now simulate the behavior of star clusters over 10 billion years, accounting for every single star in the cluster. No longer are approximations necessary.
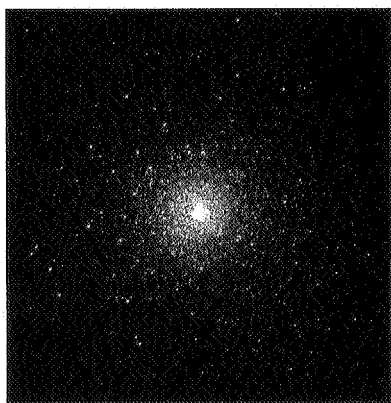

Figure 3

We're working with the full count of more than 100,000 stars. This is made possible by a new generation of computer boards that are specifically hardwired for Newton's laws, enabling these computers to solve the cluster problem faster than would the fastest all-purpose computers in the world. By some definitions, we no longer have a simulation. It's no longer an approximation of reality—it *is* reality. For astrophysicists, this represents a computational luxury without precedent.

Moore's law finally brought us closure on an important astrophysical problem. However, many other cosmic domains pose seemingly intractable problems. One of the more famous images to come from the Hubble Telescope hails from the inner part of the Eagle nebula. The so-called Pillars of Creation seen in Fig. 4 enshroud fresh regions of star formation. What we have is a stellar nursery where stars are being born along with associated planets.

It's one thing to have stars that just move cleanly under the influence of Newton's laws of gravity and motion. But now you have clouds. Not just ordinary gas clouds, but ionized gas clouds in which the rules of magnetohydrodynamics apply and turbulent motion reigns. Of course our ionized gas cloud is not isolated. It orbits the Milky Way galaxy where there are other gas clouds with which it occasionally collides. When they collide supersonically (as they typically do), shock waves ensue that rip through the plasma. Furthermore, the galaxy has a magnetic field, and as you may know, magnetic fields can influence the motion and behavior of plasma because of all those free electrons and ions running around. Long gone is the meaningful influence of your clean gravity equations. The plasma grabs onto the magnetic field and torques it in ways that interfere with the clean gravity equations. Meanwhile, some parts of the gas cloud are collapsing to make stars.

This is complicated stuff. We just graduated from 2-D simulations (the poor man's solution) a few years ago. Yes, we just removed one of the spatial dimensions to save computing time in this multivariate problem. There's an unwritten rule in astrophysics: your computer simulation must end before you die. Only recently has the power of computing enabled us to think about this problem in 3-D. Our problems extend far beyond star clusters and gas clouds within our gal-
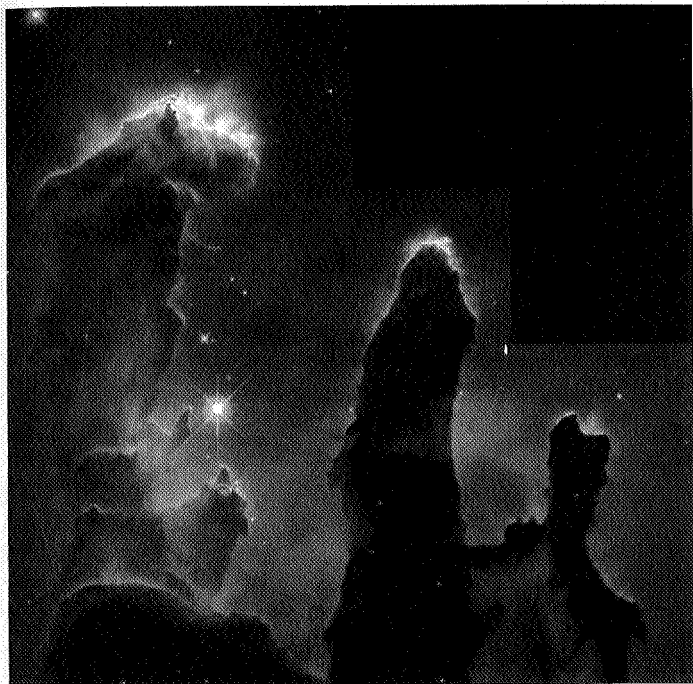
Figure 4

axy. Some of us care about what happens to whole galaxies. In Fig.
5, we have a negative print (for enhanced contrast) of galaxies
caught in the act of colliding. Actually, the word *caught* slightly
overstates it. Galaxies, when they collide, take a couple of hundred
million years to do so. Regardless, these are sorry-looking systems.
They were once spiral galaxies—beautiful and symmetric—minding
their own business, until something came slamming into them,
wreaking havoc on their structures, their forms, and on their iden-
tities.

By the way, our Milky Way galaxy is on a collision course with
the Andromeda galaxy. We will likely collide with it and end up
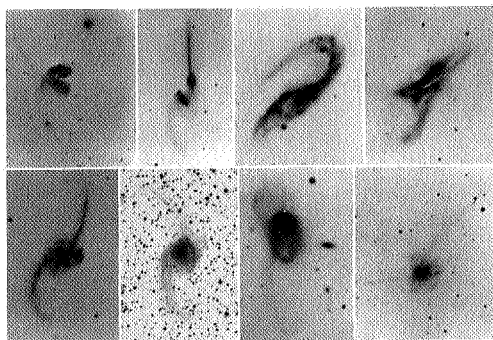looking like some of the galaxies in Fig. 5. No need to worry. We

Figure 5

have top people working on the problem who assure us it will not happen for another 7 billion years.

And what a difference a decade makes. In a simulation of colliding galaxies from 1992, only a few thousand stars could be modeled and we had to leave out the gas. Recently, however, on a run conducted by the IBM Blue Horizon machine at the San Diego Supercomputer Center, a billion stars were modeled, making for a much smoother and realistic portrayal of these important events in the real universe.

Inside our new space theater (Fig. 6), we have seven video projectors, each with a footprint that perfectly tiles the hemisphere in such a way that you're completely immersed in whatever three-dimensional data happens to live on the computer. For part of our inaugural space show titled, "Passport to the Universe," another calculation was done at the San Diego Supercomputer Center. For this segment we journey through the Orion nebula, another stellar nursery where stars are being born in our galaxy.

The calculations and renderings were not simple placements of stars with a flyby. The cloud is variably transparent and variably colored as you move through it. This is the astrophysics of the cloud. All this was rendered at HD resolution in 30 frames per second over 7 channels for 5 minutes. This particular journey was a path through static data. What we really want to do one day is evolve the gas and the stars within it while we move through the system.

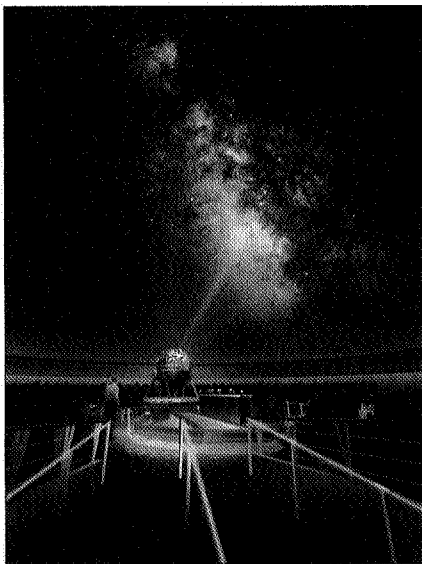By the way, there are only about 6000 astrophysicists in the world.

Figure 6

With a world population of about 6 billion people, we're about one in a million. So if you ever sit next to one on an airplane, ask all the cosmic questions you have because you never know when such an educational opportunity will arise again. Meanwhile, back at our labs, we are awash in data. With large digital detectors mounted at the business end of large telescopes in orbit and on the ground, we are conducting large-scale surveys of the sky, generating countless terabytes of data with every sunrise. For each of the past 4 decades, astrophysicists have collaborated and produced a book listing our funding priorities for Congress in the decade that follows. When Congress reviews the document, they see a unified front—no public bickering or infighting over major projects (that all happens behind closed doors during the production of the book). The Hubble Space Telescope (HST) came out of such planning. So too did the celebrated Very Large Array (VLA) of radio telescopes in Socorro, New Mexico. Did you know that the highest-priority items in the document for the first decade of the twenty-first century did not include

a major expensive observatory? What it did contain is what we are calling a National Virtual Observatory (NVO). For the first time, we are recognizing that the data are coming in faster than we can analyze them. Somehow we must find a way to democratize the data for maximum benefit to researchers and to our understanding of the cosmos.

The way it could work is by setting up agreed-upon parameters by which we take our data from individuals' telescopes and feed these data to a major central data bank. The bank, over time, becomes the universe itself, available for all to peruse. In this model, instead of vying for time on a telescope, you apply for time to observe the meta–data set of the universe. Or perhaps you do not apply for time at all because, unlike time on a telescope, access to data is in principal unlimited. All you need is high-bandwidth Internet access. You don't even have to leave your office. You can observe a patch of the sky and compare it with patches from other telescopes. As you know, we observe the universe at all wavelengths: radio waves, X rays, gamma rays, infrared, and so forth. For any patch of sky, I could query the data for its infrared as well as radio wave information and compare them. You query the universe, with the computer as your telescope. Such a coordinated plan is without precedence in our community, and we are all very excited about it. We are nonetheless still grappling with how to design it and make it work. In some ways it's a bigger project than the Hubble Space Telescope. For the Hubble, you pour the glass, grind the mirrors, build and attach the detectors, slap the telescope into the shuttle bay, and into orbit it goes. Not to diminish the engineering achievement that Hubble represents, but we've built telescopes before. We've launched stuff into orbit before. The NVO? We've never been there before, so we are groping in the dark at the moment. For this reason, we might come knocking on your info-tech doors to get some advice on data acquisition, management, and access.

Let's return for the moment to the 15-year doubling time for publication in astrophysics. At the time I made this observation in the Princeton Library, I paused and asked the next obvious question. If half the wall covers 15 years, suppose I had performed this same experiment in 1985. What would I have measured? So I did the

experiment again. Covering up where I just walked, I found the halfway point between the beginning of the journals and 1985. Do you know where it was? 1970. Then I did it for 1970. You know where it was? 1956. Did it again. The halfway point went back to 1940. This trend continued, plus or minus a year or two, back to the beginning. At that moment I realized something. Here we all are, standing in praise of Moore's law as a catalyst in cosmic discovery, yet some other phenomenon is at work. It's not that today we live in the golden age of cosmic discovery. It's that the entire century was (and continues into the next century) a golden age of cosmic discovery. Before there was Moore's law or before there were computers playing an important role in scientific discovery, how do we account for this sustained exponential growth in the field? What forces preceded Moore's law?

Surely the photocopier had an important effect. We take it for granted today, but in the old days you had to reserve library time in your daily schedule to read the journal of interest. For the years that followed the introduction of the photocopier, you could just walk in, photocopy the journal pages of interest, and take them with you. The art of reading journals could then be time-shifted to the convenience of the reader. Think of how that must have felt at the time—how much freedom it brought. And right now, of course, on my laptop, I just download research papers (or are they research electrons?) of my choice from central repositories, without my laptop getting any heavier. These research papers were deposited days or even hours before I read them.

I'm not here to predict if and when Moore's law will crack. All I know is that the exponential growth of science has been going strong for at least the past 150 years. Before Maxwell's equations. Before Einstein's relativity. Before quantum mechanics. Before the expanding universe. My evidence comes from how authors boasted of what was known in their day. For example: "Now, in the history of the human intellect, there's no more astonishing chapter than that concerned with the sidereal, stellar researches of the last quarter century." (Agnes Clerke, *The System of the Stars*, 1890)

Yes, they were waxing poetic in 1890. We're neither unique nor special. We think we're hot because we have computers and they

didn't. What matters here is that they had stuff that the people 100 years before them didn't have. Let's go back even further. In a review of scientific discovery, the preface boasts:

> The progress of invention and discovery of improvement and application is so rapid, unceasing and continuous, that it would require a volume many times the size of the present, to record, even in a summary fashion, all that transpires of scientific interest in the course of a single year.
> —David A. Wells, *Annual of Scientific Discovery*, 1852

You know what they talked about in that volume? The year 1851 was the first demonstration of the Foucault Pendulum, on which there is an entire chapter. No one had ever directly measured the rotation of Earth. We might even try to get one for the home, showing off to neighbors how far science has come. Mr. Wells continues:

> One fact must be apparent to us all. That is the number of persons now engaged in, contributing to the advance of every department of natural physical science, is greater than at any former period. The evidence of this is to be found in the greatly increased publication and circulation of scientific books and journals.

What's going on? What do we do now, armed with this insight of time? We're going to get old and tired, and the next generation is going to take our place. The last time I looked out my window, I spotted the youth of today. They were skateboarding, with tattoos on their butts, and pierced belly buttons. I am now reminded of a famous quote on the youth of the day: "The earth is degenerating these days. Bribery and corruption abound. Children no longer mind parents. And it is evident the end of the world is approaching fast." (Syrian tablet, 2800 B.C.)

Listen, if the youth of today were as bad as we always said they were—at every succeeding generation—there'd be no society. We'd all be devolved and living in caves. As adults, we must be missing something. Why is it that America leads the world in innovations?

I think I know why. When you ride a skateboard, pierce nonstandard body parts, and get butt tattoos, it means you are not in somebody's box. And where do innovations come from? They come from outside, not inside, the box. My 4½-year-old daughter, she doesn't even know how to turn on the TV by touching it. Instead, she commands three remote controls and routinely says, "Daddy, I'm going to play the DVD now. Do you want to join me?" No. I'm not so worried about the youth. They're going to make it just fine. And I'll tell you something else. That generation has unprecedented access to science because it's everywhere. News headlines about science are almost as frequent as headlines about politics. My memories from growing up in the 1960s and 1970s do not include how much science made the news. Yes, we had some space program headlines, but there wasn't much science in it—only the undercurrent of "Let's beat the Russians."

Although I am somewhat biased, allow me to share one of my favorite quotes, which hails from 300 years ago:

> Of all the science cultivated by mankind, astronomy is acknowledged to be and undoubtedly is, the most sublime and the most interesting. For by knowledge derived from this science, not only the bulk of the earth is discovered, but our faculties are enlarged, with the grandeur of the ideas it conveys, our minds exalted above the low contracted prejudices of the vulgar.
> —James Ferguson, *Astronomy Explained Upon Sir Isaac Newton's Principles*, 1757

Perhaps if the field of information technology were around back then, Mr. Ferguson would have written about that. When the Rose Center opened, articles appeared in *Popular Science* and *Scientific American*, as you might expect. But the place also earned a photo shoot in *Vogue*, in *Welding Quarterly*, and in the *Wine Spectator*. And our controversial treatment of Pluto and its planet status in the solar system was a cover story in the *New York Times*—2 days after Bush's inauguration. What does distinguish scientific discovery today from yesterday is that public exposure appears to have reached

a critical mass where the fruits of science are now legitimate subjects for cocktail parties. Instead of distant observers, the public has become vicarious participants in the scientific enterprise.

I look forward to what computing power (and bandwidth) will continue to bring to the cosmic frontier, but what's fascinating about our future is what we can't predict and what role other factors might play in maintaining our doubling rate—whether or not Moore's law has any relation to the cosmos at all.