Astrophysics For People In A Hurry

Neil DeGrasse Tyson

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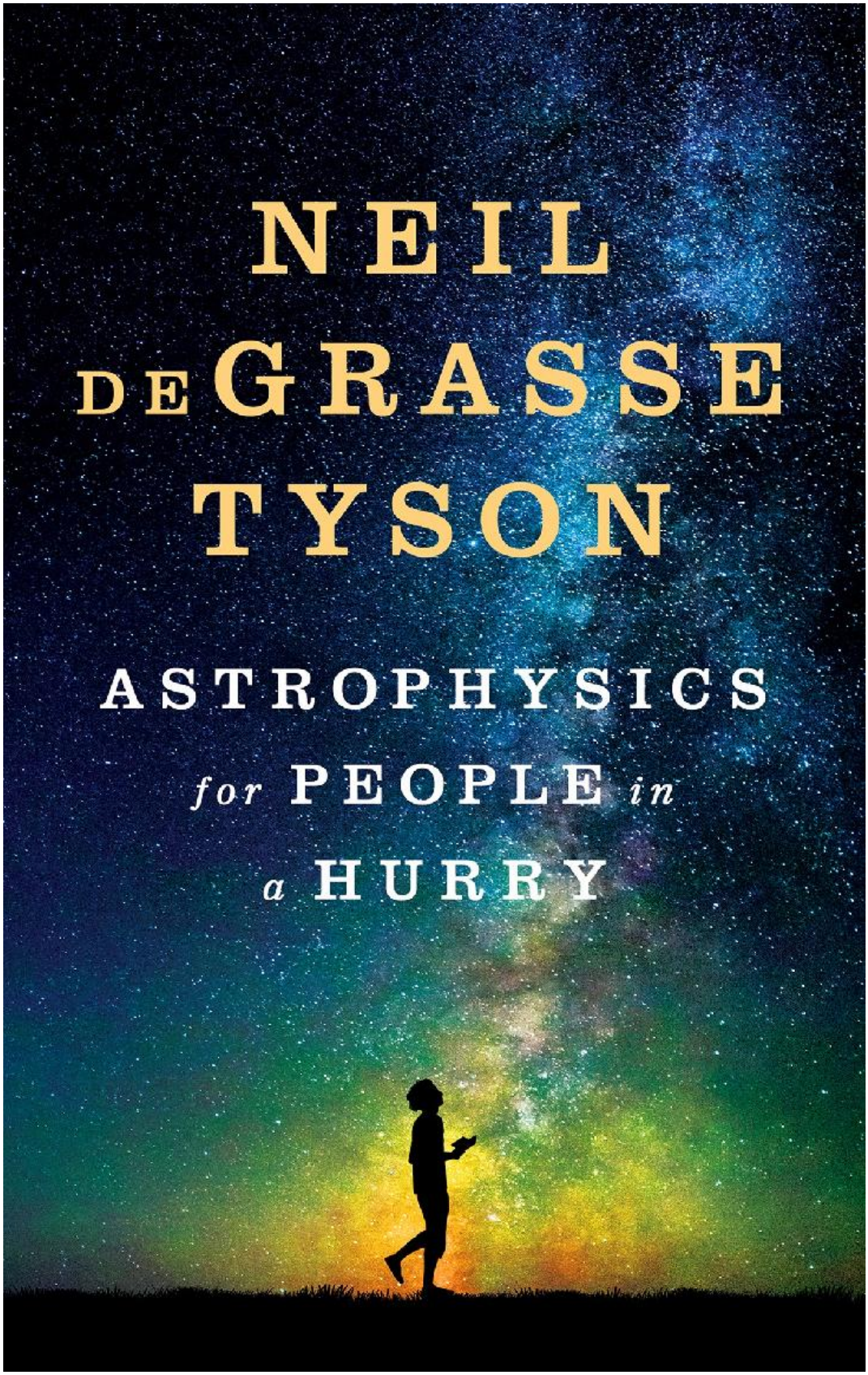
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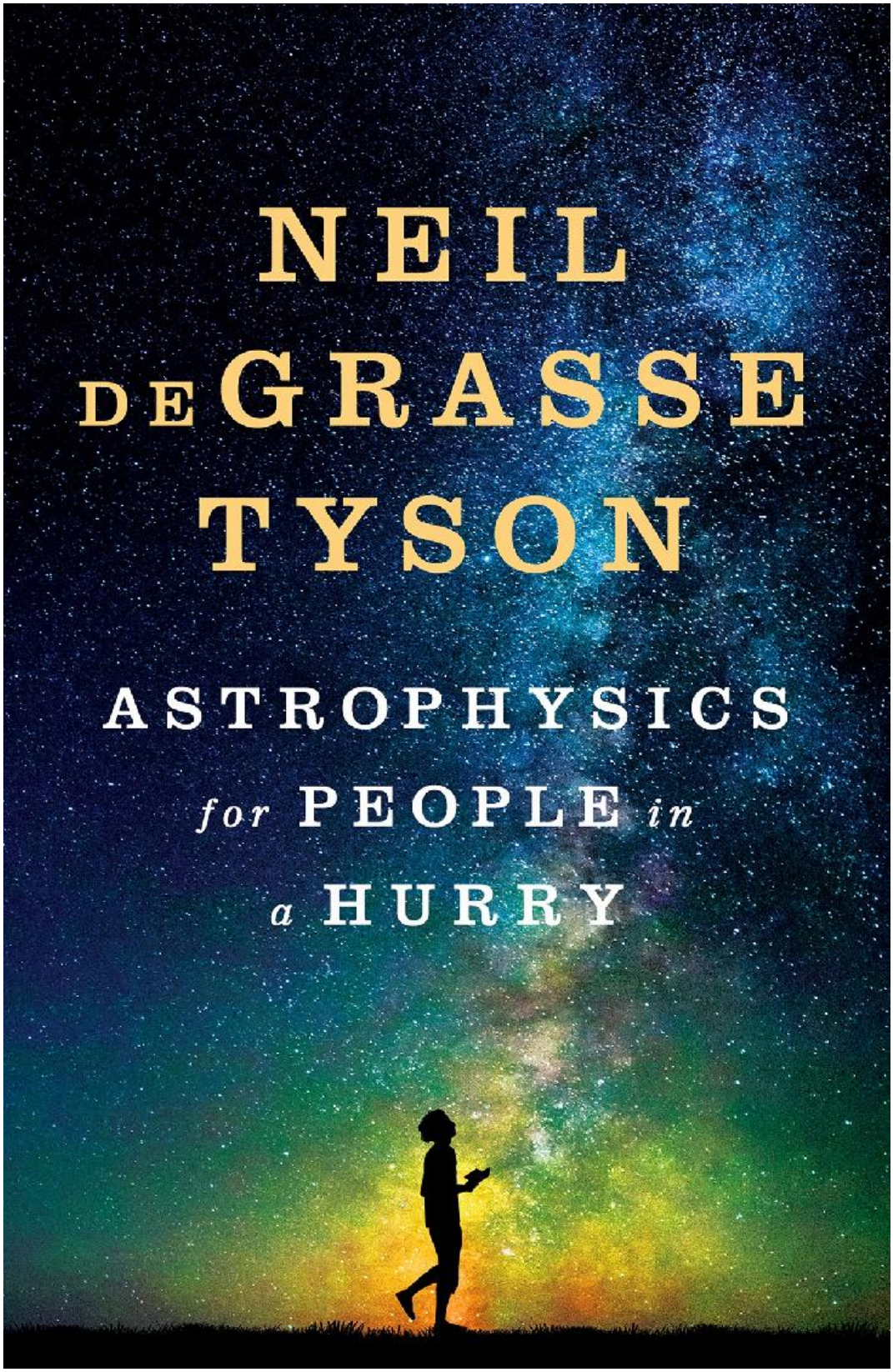
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Astrophysics for People in a Hurry

NEIL DEGRASSE TYSON

For all those who are too busy to read fat books Yet nonetheless seek a conduit to the cosmos

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PREFACE

In recent years, no more than a week goes by without news of a cosmic discovery worthy of banner headlines. While media gatekeepers may have developed an interest in the universe, this rise in coverage likely comes from a genuine increase in the public's appetite for science. Evidence for this abounds, from hit television shows inspired or informed by science, to the success of science fiction films starring marquee actors, and brought to the screen by celebrated producers and directors. And lately, theatrical release biopics featuring important scientists have become a genre unto itself. There's also widespread interest around the world in science festivals, science fiction conventions, and science documentaries for television.

The highest grossing film of all time is by a famous director who set his story on a planet orbiting a distant star. And it features a famous actress who plays an astrobiologist. While most branches of science have ascended in this era, the field of astrophysics persistently rises to the top. I think I know why. At one time or another every one of us has looked up at the night sky and wondered: What does it all mean? How does it all work? And, what is my place in the universe?

If you're too busy to absorb the cosmos via classes, textbooks, or

documentaries, and you nonetheless seek a brief but meaningful introduction to the field, I offer you *Astrophysics for People in a Hurry*. In this slim volume, you will earn a foundational fluency in all the major ideas and discoveries that drive our modern understanding of the universe. If I've succeeded, you'll be culturally conversant in my field of expertise, and you just may be hungry for more.

The universe is under no obligation to make sense to you.

—NDT

Astrophysics for People in a Hurry

1.

The Greatest Story Ever Told

The world has persisted many a long year, having once been set going in the appropriate motions. From these everything else follows.

LUCRETIUS, C. 50 BC

In the beginning, nearly fourteen billion years ago, all the space and all the matter and all the energy of the known universe was contained in a volume less than one-trillionth the size of the period that ends this sentence.

Conditions were so hot, the basic forces of nature that collectively describe the universe were unified. Though still unknown how it came into existence, this sub-pinpoint-size cosmos could only expand. Rapidly. In what today we call the big bang.

Einstein's general theory of relativity, put forth in 1916, gives us our modern understanding of gravity, in which the presence of matter and energy curves the fabric of space and time surrounding it. In the 1920s, quantum mechanics would be discovered, providing our modern account of all that is small: molecules, atoms, and subatomic particles. But these two understandings of nature are formally incompatible with one another, which set physicists off on a race to blend the theory of the small with the theory of the large into a single coherent theory of quantum gravity. Although we haven't yet reached the finish line, we know exactly where the high hurdles are. One of them is during the "Planck era"

of the early universe. That's the interval of time from $t = 0$ up to $t = 10^{-43}$ seconds (one ten-million-trillion-trillion-trillionths of a second) after the beginning, and before the universe grew to 10^{-35} meters (one hundred billion trillion-trillionths of a meter) across. The German physicist Max Planck, after whom these

unimaginably small quantities are named, introduced the idea of quantized energy in 1900 and is generally credited as the father of quantum mechanics.

The clash between gravity and quantum mechanics poses no practical problem

for the contemporary universe. Astrophysicists apply the tenets and tools of general relativity and quantum mechanics to very different classes of problems.

But in the beginning, during the Planck era, the large was small, and we suspect there must have been a kind of shotgun wedding between the two. Alas, the vows

exchanged during that ceremony continue to elude us, and so no (known) laws of

physics describe with any confidence the behavior of the universe over that time.

We nonetheless expect that by the end of the Planck era, gravity wriggled loose from the other, still unified forces of nature, achieving an independent identity nicely described by our current theories. As the universe aged through 10^{-35} seconds it continued to expand, diluting all concentrations of energy, and what remained of the unified forces split into the "electroweak" and the "strong nuclear" forces. Later still, the electroweak force split into the electromagnetic and the "weak nuclear" forces, laying bare the four distinct forces we have come to know and love: with the weak force controlling radioactive decay, the strong force binding the atomic nucleus, the electromagnetic force binding molecules, and gravity binding bulk matter.

A trillionth of a second has passed since the beginning.

All the while, the interplay of matter in the form of subatomic particles, and energy in the form of photons (massless vessels of light energy that are as much waves as they are particles) was incessant. The universe was hot enough for these photons to spontaneously convert their energy into matter-antimatter particle pairs, which immediately thereafter annihilate, returning their energy back to photons.

Yes, antimatter is real. And we discovered it, not science fiction writers. These transmogrifications are entirely prescribed by Einstein's most famous equation: *E*

= *mc2*, which is a two-way recipe for how much matter your energy is worth, and how much energy your matter is worth. The *c2* is the speed of light squared—a huge number which, when multiplied by the mass, reminds us how much energy you actually get in this exercise.

Shortly before, during, and after the strong and electroweak forces parted company, the universe was a seething soup of quarks, leptons, and their antimatter siblings, along with bosons, the particles that enable their interactions. None of

these particle families is thought to be divisible into anything smaller or more basic, though each comes in several varieties. The ordinary photon is a member of the boson family. The leptons most familiar to the non-physicist are the electron and perhaps the neutrino; and the most familiar quarks are . . . well, there are no familiar quarks. Each of their six subspecies has been assigned an abstract name that serves no real philological, philosophical, or pedagogical purpose, except to distinguish it from the others: *up* and *down*, *strange* and *charmed*, and *top* and *bottom*.

Bosons, by the way, are named for the Indian scientist Satyendra Nath Bose.

The word "lepton" derives from the Greek *leptos*, meaning "light" or "small."

"Quark," however, has a literary and far more imaginative origin. The physicist Murray Gell-Mann, who in 1964 proposed the existence of quarks as the internal

constituents of neutrons and protons, and who at the time thought the quark family had only three members, drew the name from a characteristically elusive line in James Joyce's *Finnegans Wake*: "Three quarks for Muster Mark!" One thing quarks do have going for them: all their names are simple

—something chemists, biologists, and especially geologists seem incapable of achieving when naming their own stuff.

Quarks are quirky beasts. Unlike protons, each with an electric charge of +1,

and electrons, with a charge of –1, quarks have fractional charges that come in thirds. And you'll never catch a quark all by itself; it will always be clutching other quarks nearby. In fact, the force that keeps two (or more) of them together actually grows stronger the more you separate them—as if they were attached by

some sort of subnuclear rubber band. Separate the quarks enough, the rubber band snaps and the stored energy summons $E = mc2$ to create a new quark at each end, leaving you back where you started.

During the quark–lepton era the universe was dense enough for the average separation between unattached quarks to rival the separation between attached quarks. Under those conditions, allegiance between adjacent quarks could not be unambiguously established, and they moved freely among themselves, in spite of

being collectively bound to one another. The discovery of this state of matter, a kind of quark cauldron, was reported for the first time in 2002 by a team of physicists at the Brookhaven National Laboratories, Long Island, New York.

Strong theoretical evidence suggests that an episode in the very early universe, perhaps during one of the force splits, endowed the universe with a remarkable asymmetry, in which particles of matter barely outnumbered particles of antimatter: by a billion-and-one to a billion. That small difference in population would hardly get noticed by anybody amid the continuous creation, annihilation, and re-creation of quarks and antiquarks, electrons and antielectrons (better

known as positrons), and neutrinos and antineutrinos. The odd man out had oodles of opportunities to find somebody to annihilate with, and so did everybody else.

But not for much longer. As the cosmos continued to expand and cool, growing

larger than the size of our solar system, the temperature dropped rapidly below a trillion degrees Kelvin.

A millionth of a second has passed since the beginning.

This tepid universe was no longer hot enough or dense enough to cook quarks,

and so they all grabbed dance partners, creating a permanent new family of heavy particles called hadrons (from the Greek *hadros*, meaning "thick"). That quark-to-hadron transition soon resulted in the emergence of protons and neutrons as well as other, less familiar heavy particles, all composed of various combinations of quark species. In Switzerland (back on Earth) the European particle physics collaboration† uses a large accelerator to collide beams of hadrons in an attempt to re-create these very conditions. This largest machine in the world is sensibly called the Large Hadron Collider.

The slight matter–antimatter asymmetry afflicting the quark–lepton soup now passed to the hadrons, but with extraordinary consequences.

As the universe continued to cool, the amount of energy available for the spontaneous creation of basic particles dropped. During the hadron era, ambient photons could no longer invoke $E = mc2$ to manufacture quark–antiquark pairs.

Not only that, the photons that emerged from all the remaining annihilations lost energy to the ever-expanding universe, dropping below the threshold required to create hadron–antihadron pairs. For every billion annihilations —leaving a billion photons in their wake—a single hadron survived. Those loners would ultimately

get to have all the fun: serving as the ultimate source of matter to create galaxies, stars, planets, and petunias.

Without the billion-and-one to a billion imbalance between matter and

antimatter, all mass in the universe would have self-annihilated, leaving a cosmos made of photons *and nothing else*—the ultimate let-there-be-light scenario.

By now, one second of time has passed.

The universe has grown to a few light-years across, ☥☥ about the distance from the Sun to its closest neighboring stars. At a billion degrees, it's still plenty hot—

and still able to cook electrons, which, along with their positron counterparts, continue to pop in and out of existence. But in the ever-expanding, ever-cooling universe, their days (seconds, really) are numbered. What was true for quarks, and true for hadrons, had become true for electrons: eventually only one electron in a billion survives. The rest annihilate with positrons, their antimatter sidekicks, in a sea of photons.

Right about now, one electron for every proton has been "frozen" into existence. As the cosmos continues to cool—dropping below a hundred million degrees—protons fuse with protons as well as with neutrons, forming atomic nuclei and hatching a universe in which ninety percent of these nuclei are hydrogen and ten percent are helium, along with trace amounts of deuterium ("heavy" hydrogen), tritium (even heavier hydrogen), and lithium.

Two minutes have now passed since the beginning.

For another 380,000 years not much will happen to our particle soup.

Throughout these millennia the temperature remains hot enough for electrons to roam free among the photons, batting them to and fro as they interact with one another.

But this freedom comes to an abrupt end when the temperature of the universe

falls below 3,000 degrees Kelvin (about half the temperature of the Sun's surface), and all the free electrons combine with nuclei. The marriage leaves behind a ubiquitous bath of visible light, forever imprinting the sky with a record of where all the matter was in that moment, and completing the formation of particles and atoms in the primordial universe.

For the first billion years, the universe continued to expand and cool as matter gravitated into the massive concentrations we call galaxies. Nearly a hundred billion of them formed, each containing hundreds of billions of stars that undergo thermonuclear fusion in their cores. Those stars with more than about ten times the mass of the Sun achieve sufficient pressure