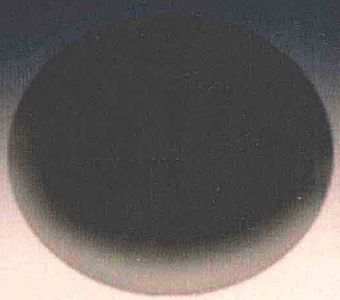
# WORLDS UNNUMBERED

## THE SEARCH FOR EXTRASOLAR PLANETS

Donald Goldsmith



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# *Worlds Unnumbered*

THE SEARCH FOR EXTRASOLAR PLANETS

*For Rachel—*
*and for all*
*who seek new worlds*

# *Preface*

Human fascination with other worlds has a long history, resonating deeply with our desire to connect with the universe that brought us here. During the past few decades, while exploring the sun's own family of planets, astronomers have dreamt of the day when they would find what other planets circle other suns. However, the immense distances between the stars made the discovery of these planets impossible. Until now: In October 1995 astronomers found the first planet orbiting a sunlike star. The next twelve months brought half a dozen more planets to light; before the turn of the millennium, several dozen more may well be discovered.

But these planets confounded expectation. They have large masses, comparable to the mass of Jupiter, the sun's largest and most massive planet. This much astronomers expected, because the methods used to find them favor the discovery of large planets. However, half of the newfound planets orbit their stars at tiny distances, less than one-sixth of the distance from the sun to Mercury, its innermost planet. Even though the search technique also favored finding close-in planets, no one anticipated that Jupiter-like planets could exist so close to their stars as this. All theories of planet formation imply that these massive planets must have formed a hundred times farther out and somehow migrated inward to reach their present distances from their stars. This is just one of the conundrums posed by the new discoveries of extrasolar planets, which will stimulate inquiries into planet formation for years to come.

In this book, I have attempted to describe the recent planet discoveries and their manifold implications, which range over theories of planet formation, our understanding of life in the universe, the difficulties of observing extrasolar planets, and the prospects for future planet discoveries. Within a short time, extrasolar planets have made the transition from "a subject with no subject matter" to a rapidly expanding area of astronomical research, one of the most important in modern astronomy. I hope that my book captures some of the excitement, as well as the scientific facts of life (see the Glossary for terms italicized in the text) that underlie humanity's current efforts to find new worlds and thus to achieve a better understanding of our solar system and our home planet.

*Donald Goldsmith*
*Berkeley, California*
*September 1996*

# *Acknowledgments*

In writing this book, I have once again had the good fortune to receive helpful assistance from many friends and colleagues, who were motivated by the desire to help me avoid the most grievous errors in describing the search for extrasolar planets. Like other authors, I hope that the suggestions and warnings from those seeking to improve the text have been properly taken into account. In any case, I hereby release those cited below from any and all liability, legal, moral, or ambiguous, in connection with the preparation of this book.

My greatest thanks go to Bruce and Kathy Armbruster, who arranged for the appearance of this book and oversaw it through the publication process; they have maintained a belief in this and other projects far beyond the requirements of business. Robert Ishi gave the book its form and design, and he and Susanna Tadlock helped me through many a difficult moment in understanding the demands of book production. Fronia Simpson copy-edited the manuscript with verve. Jon Lomberg, an astronomy artist beyond easy comparison, has continued to contribute greatly to conveying scientific concepts, both in his art and by making me think more carefully about what an illustration has to say; he also made valuable comments about the manuscript. I would also like to thank Charles Beichman, Carlos Eiroa, Harley Thronson, and Jill Tarter for helping me to attend several conferences dealing with the search for extrasolar planets.

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Let us (since Life can little more supply
Than just to look about us and to die)
Expatiate free o'er all this scene of Man;
A mightly maze! but not without a plan . . .

I. Say first, of God above, or Man below,
What can we reason, but from what we know?
Of Man, what see we but his station here,
From which to reason, or to which refer?
Thro' worlds unnumber'd tho' the God be known,
'Tis ours to trace him only in our own.
He, who through vast immensity can pierce,
See worlds on worlds compose one universe,
Observe how system into system runs
What other planets circle other suns,
What varied Being peoples ev'ry star,
May tell why Heav'n has made us as we are.

—Alexander Pope, *An Essay on Man* (1733)

# *Contents*

CHAPTER

# 1

# *What New Worlds Are These?*

On January 17, 1996, at the winter meeting of the American Astronomical Society in San Antonio, Texas, two astronomers from San Francisco State University, Paul Butler and Geoff Marcy, announced their discovery of two new planets, each of them orbiting a star much like our sun and (in astronomical terms) close to our own solar systems. The news fell on the astronomically inclined public like welcome rain on parched earth: At long last, after decades of searching, astronomers had found objects orbiting other stars that resemble the planets that orbit our sun. Before the month was over, Marcy and Butler found themselves named "Persons of the Week" by ABC News and featured on the cover of *Time* magazine. Their sudden prominence amazed their fellow astronomers, even though they knew that the search for planets around other stars has a special resonance with the public, since the only life we know in the universe—life on Earth—exists on a planet. Most astronomers had never dreamt that these new results would prove such a draw, elevating the search for extrasolar planets from a quiet astronomical backwater into a focus of worldwide attention.

Yet the two planets found by Butler and Marcy were *not* the first and second planets discovered around stars like the sun; in-

stead, they were the second and third (Table 1.1). More than three months before, on October 6, 1995, in Florence, Italy, two astronomers from the University of Geneva, Michel Mayor (Figure 1) and Didier Queloz, had announced to a conference—held only a stone's throw from the home where Galileo Galilei spent years under house arrest for asserting that the Earth orbits the sun—that they had found a planet orbiting the star 51 Pegasi, forty-five light years from the solar system.

During the previous few years, Mayor and Queloz had been in friendly competition with Butler and Marcy: Each pair of astronomers had long-term observing projects that studied sunlike stars over several years' time, accumulating the data that, upon computer analysis, might reveal a planet. The astronomers had chosen to search for planets orbiting sunlike stars—stars much like our own in their masses, sizes, and surface temperatures—because the light from these stars has characteristics that make searching for planets orbiting them easier than a search around stars that are significantly hotter or cooler than the sun (see page 155).

When Butler and Marcy (Figure 2) in California learned that their Swiss competitors had found a planet orbiting a star in the constellation Pegasus, they spent a long afternoon trying to guess which star had the planet, and why they had failed to find it. Upon learning its identity, they shook their heads in dismay. The *Yale Bright Star Catalog*, a standard compilation describing several hundred thousand stars, had misclassified 51 Pegasi, listing it as significantly larger than the sun, so Butler and Marcy had dropped it from their observing list. Mayor and Queloz, who knew better, had found the first planet around another star. Electrified by the news from Florence, Butler and Marcy redoubled their efforts in observing stars and in analyzing the years of data accumulated on their computer's hard disk. Before long, they had confirmed Mayor and Queloz's discovery and had also found the two additional planets they announced in San Antonio.

Why did the initial discovery receive far less publicity than the news of two additional planets orbiting sunlike stars? A large

TABLE 1.1

**Planets Found around Other Stars by Doppler-Shift Techniques, with Earth and Jupiter for Comparison**

| *Star* | *Year of Planet's Discovery* | *Star's Mass (in units of sun's mass)* | *Planet's Minimum Mass (in units of Jupiter's mass)* | *Average Planet-Star Distance (in units of the Earth-sun distance)* | *Orbital Period (days)* | *Orbital Eccentricity (see note below)* | *Distance from Solar System (light years)* |
|---|---|---|---|---|---|---|---|
| 51 Pegasi | 1995 | 1.0 | 0.47 | 0.05 | 4.229 | 0.0 | 45 |
| 70 Virginis | 1996 | 0.9 | 6.6 | 0.43 | 116.6 | 0.40 | 72 |
| 47 Ursae Majoris | 1996 | 1.1 | 2.4 | 2.1 | 1,090 | 0.03 | 44 |
| Tau Bootis | 1996 | 1.2 | 3.9 | 0.046 | 3.31 | 0.0 | 49 |
| 55 Cancri #1 | 1996 | 0.8 | 0.8 | 0.11 | 14.76 | 0 | 44 |
| 55 Cancri #2 | 1996 | | 5 | about 7 | about 5,500 | 0 | |
| Upsilon Andromedae | 1996 | 1.2 | 0.6 | 0.04 | 4.6 | 0 | 54 |
| 16 Cygni B | 1996 | 1.0 | 1.6 | 2.2 | 810 | 0.57 | 84 |
| Sun (& Earth) | | 1.0 | 0.003 | 1.0 | 365.24 | 0.02 | |
| Sun (& Jupiter) | | 1.0 | 1.0 | 5.2 | 4332.6 | 0.05 | |

*Note:* For a planet's elliptical orbit around a star, the orbital eccentricity equals the difference between the planet's greatest and least distances from the star, divided by the length of the ellipse's long axis. For a circular orbit, this ratio is zero; for a tremendously elongated ellipse, the eccentricity approaches one.

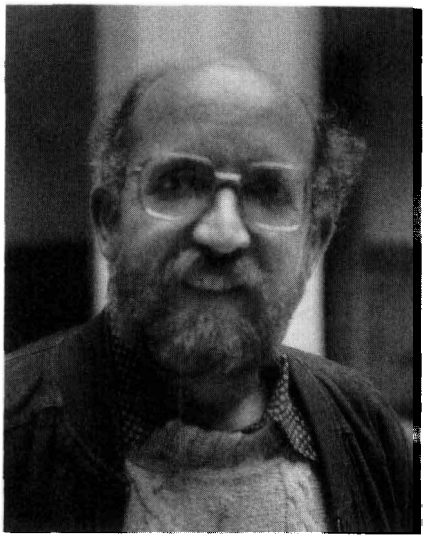

FIGURE 1 Michel Mayor of the University of Geneva is the codiscoverer of the first planet found around a sunlike star.

part of the explanation for the difference lies in Europe's distance from the United States, but some of it resides in a crucial fact about science. The most basic rules for scientific investigation of the universe imply that the discoveries of the second and third examples have greater significance than the first. *One* planet, discovered around *one* star beyond the sun, might prove a fluke, perhaps not a planet at all, perhaps explicable by stellar pulsations or by some other phenomenon only dimly understood. But when several stars display similar patterns of behavior; when that behavior can be most straightforwardly attributed to the effects of a planet moving in orbit; and when the planets deduced to exist from these effects (see page 9) are roughly similar yet differ in their masses and distances from their parent stars—then scientists can reasonably conclude that they have met a widespread phenomenon, not some fascinating but immensely unusual freak of nature. Before 1996 had ended, a number of newfound planets had risen to the point that astronomers could almost begin sta-

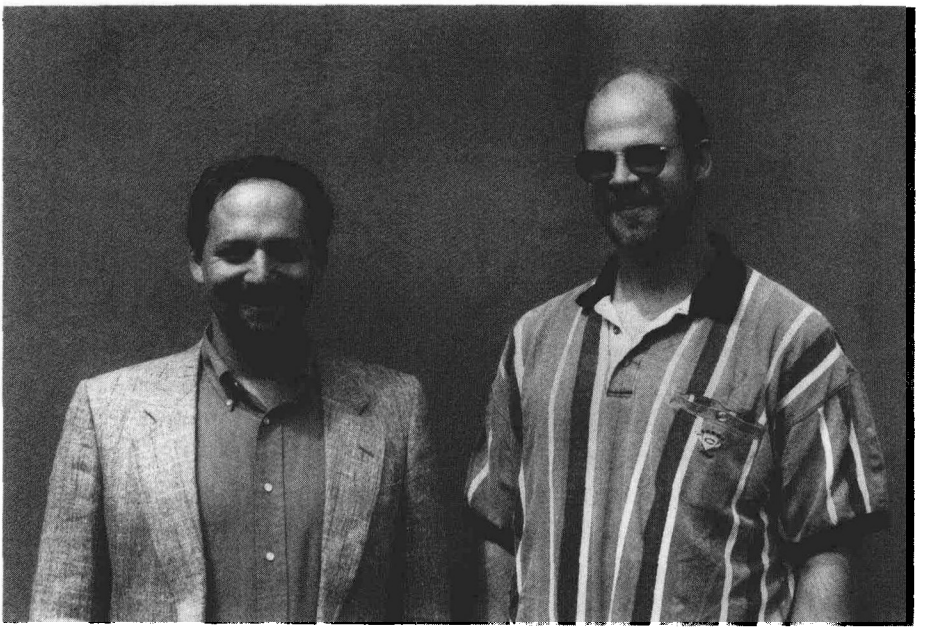

FIGURE 2 Geoff Marcy (left) and Paul Butler (right) found six of the first seven planets around stars similar to our sun.

tistical analysis of the new planets' properties—an impossibility with only a single example.

In 1733 the poet Alexander Pope recognized this principle in his famous poem *An Essay on Man*, from which an excerpt appears as this book's epigraph, by asking, "Of Man, what see we but his station here, / From which to reason, or to which refer?" Pope had hit upon the utterly valid point—often forgotten by philosophers, politicians, and poets with axes to grind—that we can draw conclusions only from what we know, but when the day arrives that we know more, why then our conclusions may change. When, a few lines later, Pope speculated about planets circling other stars, he wrote of "worlds unnumber'd." This phrase, which

I have chosen for the title of this book, underscores (at least for me) the difference between what we humans know today and what we may yet know and enumerate in the future.

Today, having numbered most of the stars within our view, we are beginning to number the worlds of which Pope dreamt. This occurs almost literally, since the stars with newly discovered planets typically have catalogue numbers such as 70 Virginis and 51 Pegasi, which refer to a list of the stars within a particular constellation. Because astronomers lovingly cling to a nomenclature system first developed during Pope's lifetime, the constellation name appears in Latin and in the genitive (possessive) case, so that 70 Virginis is star number 70 in the constellation Virgo the Virgin. The brightest individual stars in each constellation are designated by letters of the Greek alphabet: Aldebaran is Alpha Tauri, Antares is Alpha Scorpionis, and the seven stars of the Big Dipper are Alpha through Eta Ursae Majoris.

## What Do the New Planets Mean to Us?

Until 1995, amid the entire host of stars that spangle the night skies, we knew just one example of planets orbiting a star: our own solar system. Despite astronomers' steadily increasing knowledge of the sun's nine planets, of the planets' sixty-odd satellites, and of a host of sun-circling asteroids, comets, and meteoroids, we had no knowledge of planets around other stars, save for the fact that detecting any such planets presents an extremely difficult challenge. In this situation, astronomers did what comes naturally. They extrapolated from what we know about the present and past of the solar system to draw conclusions about planetary systems that might accompany stars other than the sun. Inevitably, despite their disclaimers about the unreliability of building an empire of speculation on a single example, astronomers tended to use our solar system as the representative model of what to expect around another star: smaller, rocky planets close in, giant planets farther out, with small objects moving among the planets