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SIM Lite Science Program

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ABSTRACT

We describe three versions of a notional science program for SIM Lite. With several years to launch, and with scientific advances in the meantime, these versions should be regarded as illustrative of the strength of SIM Lite's expected contributions to astrophysics. Because SIM Lite is a flexibly scheduled instrument with astrometric capabilities far in excess of the current state of the art, there are many science areas to which it can contribute. In this respect, it is an observatory like Spitzer, Hubble, or JWST, for which the scheduling is entirely driven by the peer-reviewed science that can be accomplished. But for an astrometric mission there is a practical difference from other observatories because the majority of observations comprise measurements spread over months or years and must, therefore, be preplanned. This consideration plays into how the observing program will be set up to maximize the scientific return from the mission. The three programs described here result from different assumptions about scientific priority. We fully expect that the actual program several years from now will be selected by peer review.

15.1 Committee Recommendations

SIM Life has an impressive record of endorsements from independent advisory committees. The concept of a “Space Optical Interferometer” dates from the 1981 Field Committee report — the first of three Astronomy and Astrophysics Decadal Surveys to consider precision astrometry using a targeted instrument. The Bahcall Committee report in 1991 laid out the science case for an “Astrometric Interferometer Mission.” Ten years later, a carefully crafted technical development plan (including testbeds) was in full swing, and had already showed that the goals of the Bahcall Report could likely be exceeded. This encouraged a third decadal committee (McKee-Taylor 2001) to extend the science objectives to include not just stellar and giant-planet science but also a search for rocky (perhaps habitable) planets. With almost another decade of testbeds and instrument design work since then, it is now clear that SIM Lite should be capable of detecting Earth-like planets in the habitable zones, not just around the closest few stars, but around a substantial sample. Such a database of known nearby rocky planets will be invaluable information in planning and developing next-generation instruments to perform exoplanet spectroscopy.

These three Decadal Survey committees took a very broad view, as is appropriate, of the science enabled by a precision astrometric instrument with high accuracy even on faint targets that can be pointed anywhere in the sky.

A more recent review by the Astronomy and Astrophysics Advisory Committee’s (AAAC) Exoplanet Task Force (2008) considered just one science area, albeit one of the key areas for SIM Lite; namely, the identification and characterization of Earth-like planets in the habitable zones around nearby stars — i.e., those planets for which we can reasonably expect to gather the most detailed information on their properties. The ExoPTF considered a wide range of techniques, not just astrometry, using both ground and space observatories. They concluded, in part because of the maturity of the needed technology and in part because of its comprehensiveness, that an astrometric mission should be the next major step and, as noted above, an important step in preparation for the more-challenging spectroscopy missions.

In this chapter we describe three versions of a science program (Design Reference Mission, or DRM), informed by the recommendations of these peer advisory committees. One version takes a broad view of the science of precision astrometry, with a large General Observer (GO) Program; a second program places more emphasis on exoplanets, by reserving most of the GO program for exoplanets. A third program presumes that the quest for Earth-like planets in the habitable zones should extended to a much longer star list, which requires committing the majority of the available science time. All of these use the same instrument, SIM Lite, described earlier in this book; only the observing strategies differ.

15.2 SIM Lite Mission Time

Like any space-based observatory, SIM Lite must perform a variety of functions in support of the science, as well as the actual science observations. Because SIM Lite operates differently from a conventional imager or spectrometer, it is worth outlining how the time is book-kept. In this chapter, we book-keep the time in terms of percentage of mission time, not “available” time, because the numbers are subject to revision as the mission develops (Figure 15-1).

Mission time is divided into the following four categories:

- Calibration and engineering activities, including data downlink, will require about 8 percent, preplanned and integrated with the science observations.
- Spacecraft slewing assumes there are a total of 63,000 tiles during the mission, with a small proportion of large-angle slews; this is representative, but is dependent on the details of how the science observations are scheduled.

- The astrometric grid comprises 1302 tiles, observed repeatedly during the mission (see Chapter 16) to establish a global reference frame. The reference frame is a resource that will be made available to all observers.
- Science observing time comprises the remaining time, about 69 percent. Included in science time is 2 percent assigned to the NExScI Director, as is traditional for space observatories, for urgent or exceptional science needs outside of the normal proposal process. Also included are the overheads associated with acquiring targets and reference stars in each tile (but not grid stars, which are part of the above-mentioned 9 percent). Slews between tile locations are accounted for in the 14 percent portion graphically shown in Figure 15-1.

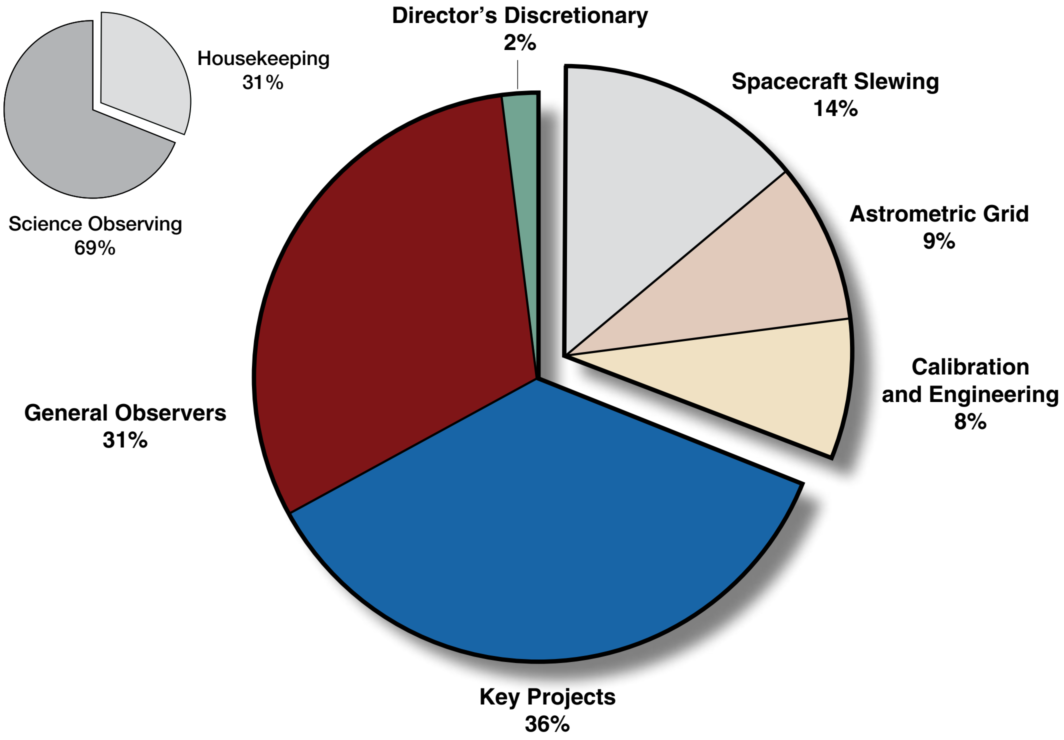


Figure 15-1. Allocation of major instrument activities on SIM Lite, averaged over the five-year mission, as a percentage of five years of mission time.

15.3 Design Reference Mission

We now describe three versions of a Design Reference Mission (DRM) for SIM Lite (Figure 15-2). There are many other possibilities, but these cover a range of criteria by which a science program may be defined. The science observations that SIM Lite will actually execute cannot be defined with any certainty at the present time — it is several years until launch, and there will undoubtedly be scientific advances and new instrumental capabilities developed in the intervening period. Stated simply, the task of selecting and executing science programs is to maximize the science return from SIM Lite. We discuss some of the considerations that go into the development of an effective science observing program.

Note that the conventional use of the term DRM is to define an instrument suite for a mission in very early development. For SIM Lite, of course, the instrument is completely defined. Its performance has been specified, and in large part verified through ground testbeds and subsystem brassboards (Chapter 18). So here we use the term DRM to refer only to possible allocations of the mission observing time.

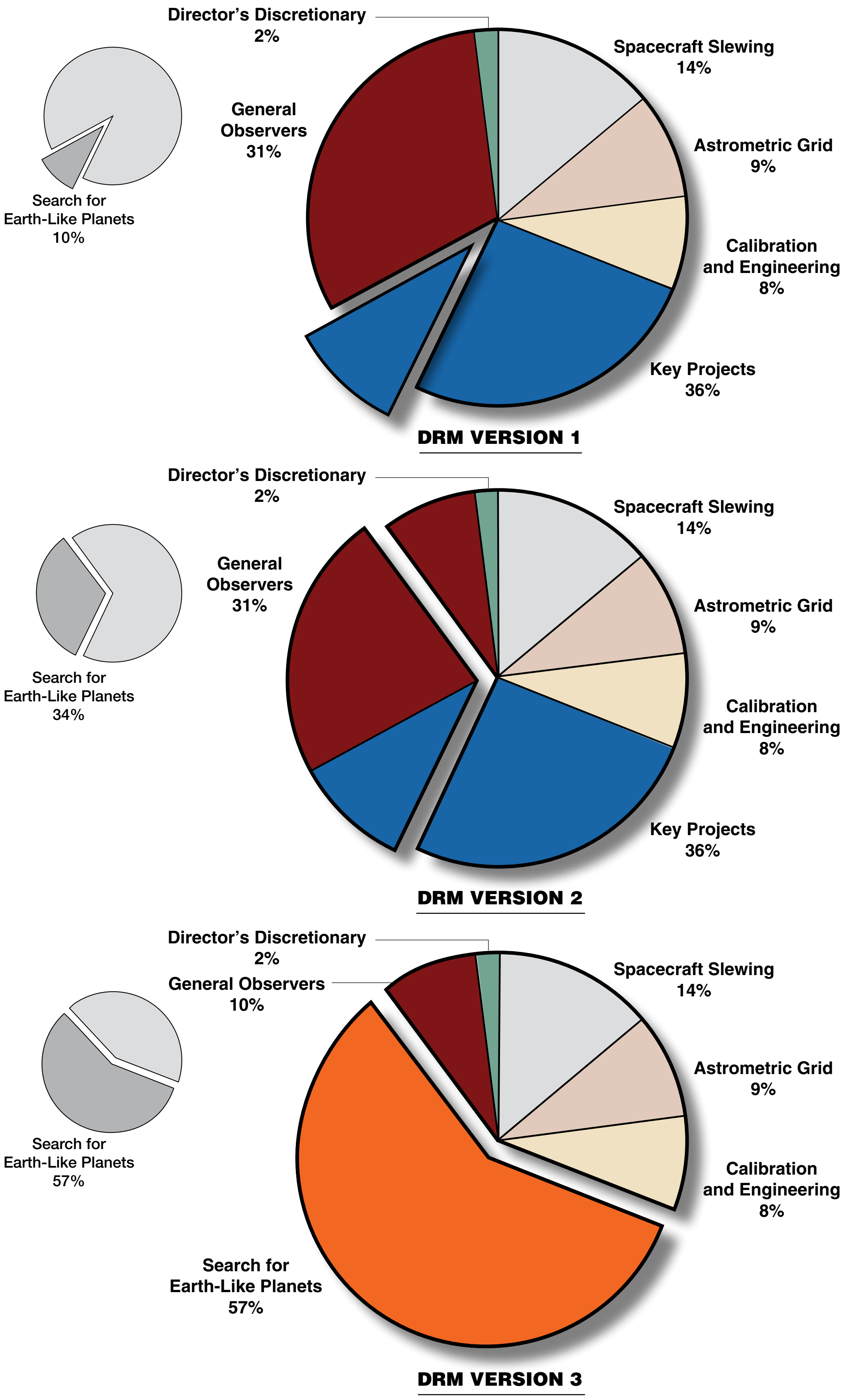


Figure 15-2. Graphical representation of three possible Design Reference Missions for SIM Lite. In DRM Version 1, the General Observer (GO) time is open. In DRM Version 2, a portion of the GO and Key Project time is allocated to (a) search for Earth-like planets, and (b) all other astrophysics. DRM Version 3 devotes almost the entire science allocation to exoplanets, so there are no Science Team Key Projects.

15.4 Design Reference Mission Version 1

The first version of the Design Reference Mission (Figure 15-3) is based on a large General Observer (GO) Program, along with the SIM Science Team Key projects. In the current science plan for SIM Lite, science observing amounts to 69 percent of the five-year mission and is divided into three categories:

- Guaranteed Time Observers (GTO) — the SIM Science Team (36 percent)
- General Observers (GO) — i.e., through a new NASA Announcement of Opportunity (31 percent)
- Director's Discretionary Time (2 percent)

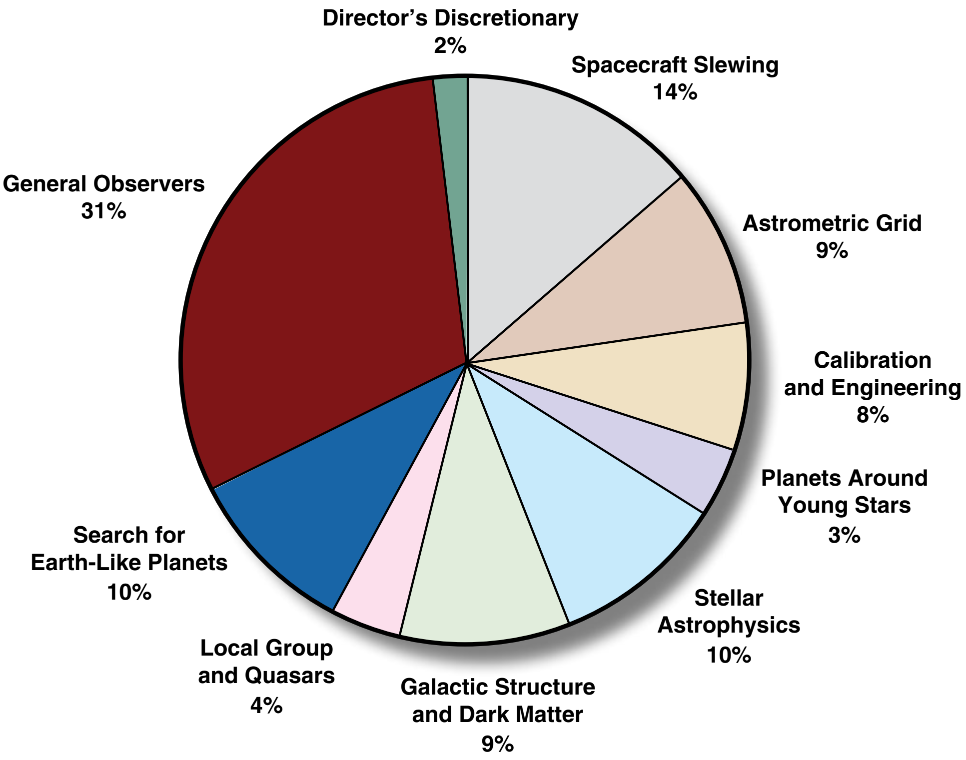


Figure 15-3. Details of the assignment of science observing time in DRM Version 1 showing the key project's allocations for specific topics.

15.4.1 Guaranteed Time Observers — The SIM Science Team

In 1999, when SIM Lite was on track for a launch in 2005, a NASA Announcement of Opportunity was issued to select the SIM Science Team. Through scientific peer review, a team of 15 members was selected, covering a wide range of possible SIM Lite science topics. Approximately half of the available observing time was assigned to large programs called Key Projects, recognizing that the scientific yield required significant up-front investment from the PIs and their teams. Proposal time demands were very high and a number of very good scientific concepts were rejected for lack of observing time.

Ten members serve as the PIs of Key Projects — major investigations requiring up to several percent of the five-year mission time. Five Mission Scientists were selected to conduct smaller programs; these individuals were chosen for their specific technical expertise relevant to the mission. The Science Team, including officially recognized co-investigators, totals 86 individuals.

The Science Team has two main functions. First, it advises the project on the development of the science program and it consults on various technical issues in instrument design, scheduling, data analysis, etc. The team played a central role in developing the formal mission Science Requirements. Since 2000, there have been over 20 formal two-day meetings of the Science Team, and numerous informal gatherings at conferences, workshops, and seminars. Second, the team

The programs of the NASA-selected 15-member SIM Science Team. For each, more details of the planned science program may be found in the chapters noted.

SIM Lite Science Team

Key Science Projects and Principal Investigators

- Discovery of Planetary Systems — *Geoffrey W. Marcy, University of California at Berkeley (Chapters 1 and 3)*
- Extrasolar Planets Interferometric Survey — *Michael Shao, JPL (Project Scientist) (Chapters 1 and 3)*
- The Search for Young Planetary Systems and the Evolution of Young Stars — *Charles A. Beichman, NExScI (Chapter 2)*
- Taking the Measure of the Milky Way — *Steven R. Majewski, University of Virginia (Chapter 4)*
- Dynamical Observations of Galaxies — *Edward J. Shaya, University of Maryland (Chapter 4)*
- Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Microlensing — *Andrew P. Gould, Ohio State University (Chapter 5)*
- Anchoring the Population II Distances and Ages of Globular Clusters — *Brian C. Chaboyer, Dartmouth College (Chapter 7)*
- Determining the Mass-Luminosity Relation for Stars of Various Ages, Metallicities, and Evolutionary States — *Todd J. Henry, George State University (Chapter 8)*
- Binary Black Holes, Accretion Disks, and Relativistic Jets: Photocenters of Nearby Active Galactic Nuclei and Quasars — *Ann E. Wehrle, Space Science Institute (Chapter 11)*
- Astrophysics of Reference Frame-Tie Objects — *Kenneth J. Johnston, U. S. Naval Observatory (Chapter 12)*

Mission Science Projects and Principal Investigators

- A New Approach to Microarcsecond Astrometry with SIM Allowing Early Mission Narrow-Angle Measurements of Compelling Astronomical Targets — *Stuart Shaklan, JPL (Chapters 1, 3, and 9)*
- Masses and Luminosities of X-Ray Binaries — *Andreas Quirrenbach, University of Heidelberg and California Institute of Technology (Chapter 9)*
- Exceptional Stars' Origins, Companions, Masses, and Planets — *Shrinivas R. Kulkarni, California Institute of Technology (Chapter 9)*
- Open and Globular Cluster Distances for Extragalactic, Galactic, and Stellar Astrophysics — *Guy Worthey, Washington State University (Chapter 10)*
- Synthesis Imaging at Optical Wavelengths with SIM — *Ronald J. Allen, Space Telescope Science Institute (Chapters 14, 16)*

conducts preparatory work, including target selection, supporting ground-based observations, theory, and modeling on the Key Projects to ensure that the best science would be obtained from the allocated time.

The Key Project and Mission Scientist programs of the Science Team form the core of the science described in earlier chapters of this book, and members of the team wrote much of this material. But there are topics that are not covered by the Key Projects. Some, like the rotational parallaxes described in Chapter 6, might be considered for inclusion as future Key Projects. Many other topics, some requiring very modest amounts of observing time, may be found among the SIM Science Studies in Chapter 13.

15.4.2 General Observer Program

Most of the remaining time (about 31 percent of the five-year mission) is planned for open community participation through a NASA Announcement of Opportunity for General Observers. This proposal call would be issued approximately two years before SIM Lite launch, and would be open to all individuals and organizations, without restriction as to scientific topic (appropriate to the instrument capabilities, of course). See Chapter 14 for details of the planned program. A small amount of time (2 percent) will also be available for later assignment as Director's Discretionary time.

15.5 Design Reference Mission Version 2

In Design Reference Mission (DRM) Version 2, we base the science on the Guaranteed Time Observer (GTO) science of the Science Team, again with a large General Observer (GO) program. Recognizing the unique role that SIM Lite will play in the search for Earth-like planets in the habitable zones (HZ) around nearby stars — those that can be followed up with spectroscopy — we assume that most of the GO time to be awarded is reserved to this search. This contrasts with DRM Version 1, for which the GO time is unrestricted as to science topic.

Two of the Key Projects, those of Marcy and Shao (Chapters 1 and 3), are devoted to searches for terrestrial exoplanets. Combining these with the reserved GO time gives a total of 33 percent of the mission devoted to planets. Figure 15-4 summarizes the observations comprising DRM Version 2. It shows the major categories of science as defined by the Science Team's Key Projects.

As a guide to the exoplanet science that this time would be used for, we start with the recommendations of the Exoplanets Task Force (2008). The ExoPTF proposed a program that searches the closest 60 stars for 1 $M_{\oplus}$ (orbiting at the inner edge of the Habitable Zone, or HZ, around 0.8 AU for a Sun-like star). This program would require about 57 percent of SIM Lite time — much more than we are allocating here, in Version 2. However, using only the notional 33 percent of SIM Lite time, we can conduct any one of the following searches (Figure 15-5):

- Search 42 stars for planets down to 1 $M_{\oplus}$ at the inner edge of the HZ.
- Search 55 stars for planets down to 1 $M_{\oplus}$ at the center of the HZ (1 AU for a Sun-like star) — very close to the ExoPTF recommendation.
- Search 70 stars for planets down to 1.5 $M_{\oplus}$ at the inner edge of the HZ.
- Search 90 stars for planets down to 1.5 $M_{\oplus}$ at the center of the HZ.

Which of these scenarios, or some combination, will SIM Lite adopt? They differ only in the "depth" of the search of each target star. There is no "right" answer, of course. Most likely the strategy would be defined by two considerations: (a) the state of knowledge at the time the targets are selected, informed

Figure 15-4. Design Reference Mission Version 2, showing the Science Team's Key Projects, a substantial General Observer program devoted to exoplanet searches, and a General Observer program (8 percent) devoted to openly competed topics in astrophysics. See also Figure 15-2.

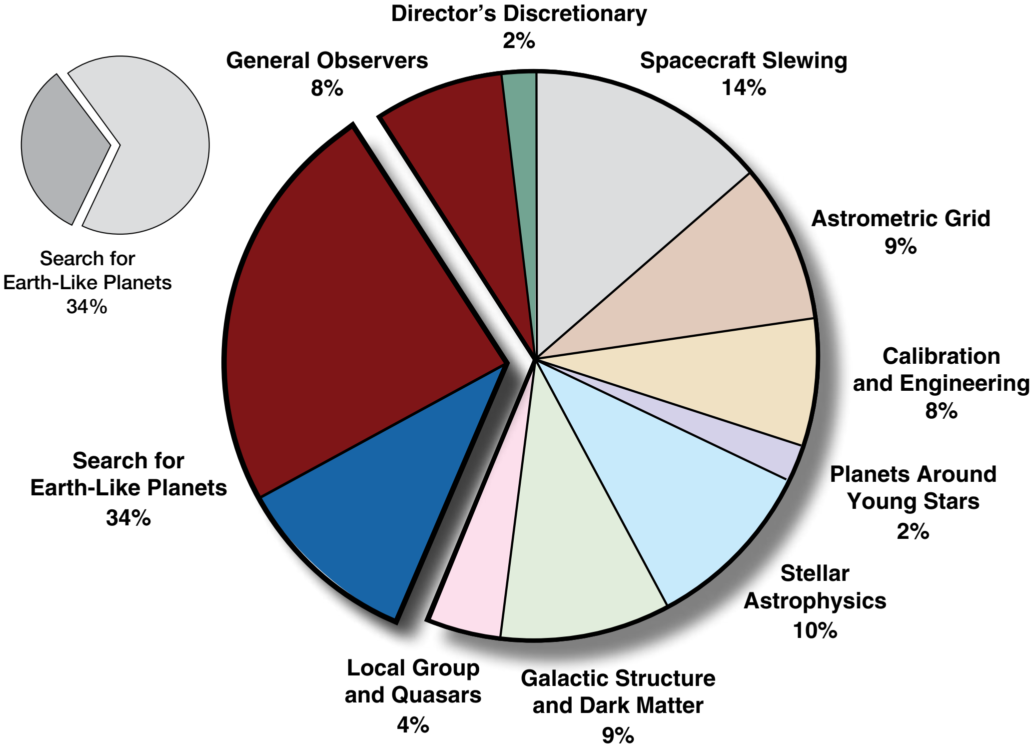
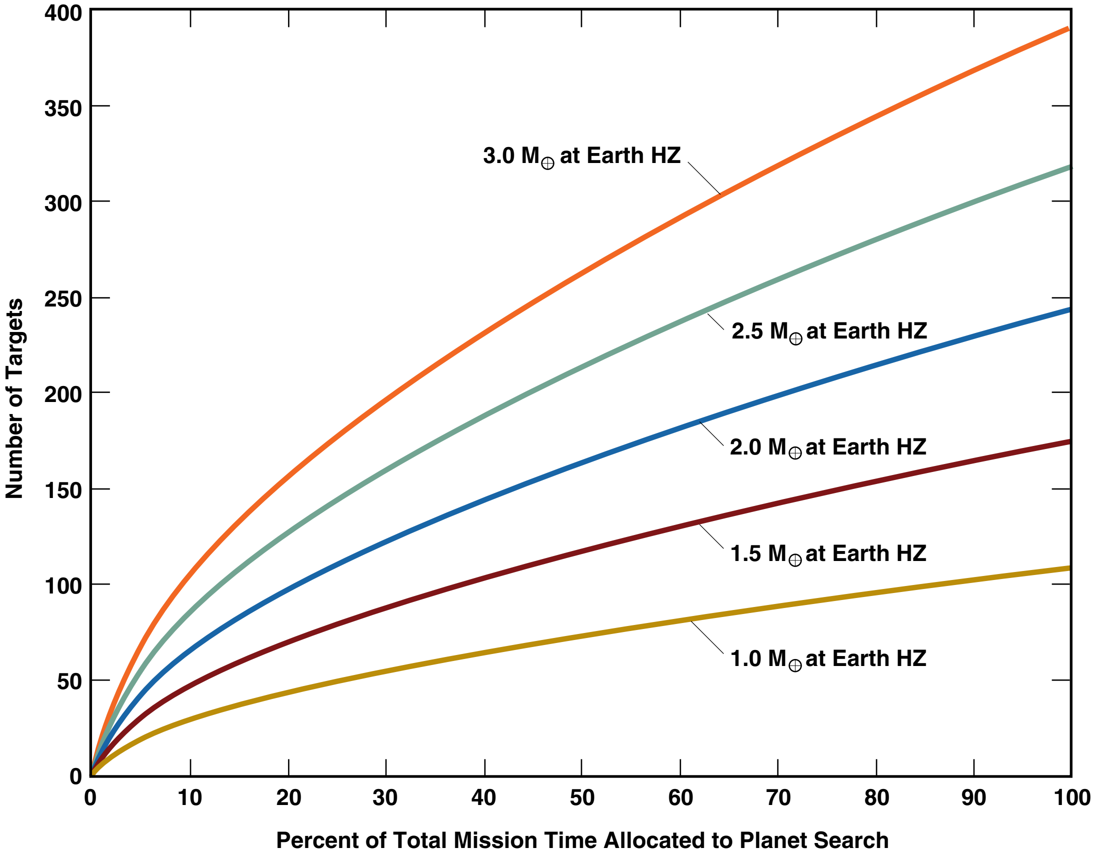


Figure 15-5. Number of nearby Sun-like stars searched by SIM Lite for Earth-like planets, as a function of observing time invested. Curves are drawn based on the mass sensitivity of various searches; for instance 1 $M_\oplus$ at the center of the HZ, for which 55 stars can be searched in 33 percent of the mission. Note that the total time available for science (Figure 15-1) is about 69 percent.



by advances in the field — results from the CoRoT and Kepler missions, better observation and modeling of the process of planet formation through observation of debris disks, and detections by other methods, including transits and microlensing experiments; and (b) peer-reviewed competition, which will take into consideration all of the above factors.

15.6 Design Reference Mission Version 3

An alternate approach to the DRM is to take the ExoPTF recommendations at face value. This can be done, but it requires substantially more observing time assigned to exoplanets than in DRM Version 2 because the more distant stars require proportionately much more time to achieve the desired search accuracy. Also note that specifying a search defined for the inner edge of the HZ is considerably more demanding than the exact same search, but specified for the center.

Taking the search criteria as 1 $M_\oplus$ at the inner edge of the HZ for a list of 60 stars, as recommended by the ExoPTF, requires 57 percent of the total mission time (Figure 15-2). There are several points to note about an assignment of observing time made in this way:

- Planet searching consumes almost all of the available SIM Lite time and it becomes almost a planets-only mission.
- Only 10 percent of the mission, plus 2 percent for Director's time, is available for all of the astrophysics, roughly equivalent to two Key Projects.
- Most of the SIM Lite time assigned to the SIM Science Team would have to be returned to the "pool" to be re-competed in a competition dedicated solely to exoplanet searches.
- Mission time devoted to a search at 1 $M_\oplus$ at the inner edge of the HZ is very "flat" in observing time (Figure 15-5); that is, the number of targets to which this depth is reached grows only slowly with observing time.
- DRM Version 2 achieves qualitatively the same exoplanet science, and provides bigger opportunities for astrophysics research.

15.7 Conclusions

Three versions of a Design Reference Mission for SIM Lite are presented above. The first represents an open approach to the science program: the Science Team programs were selected from an unrestricted proposal call; and the General Observer call would be similarly unrestricted. The second version presumes that some of the GO time will be reserved for proposals in the field of exoplanet searches. A third version assumes that almost the entire mission is devoted to exoplanets.

In Version 1, only 10 percent is assigned to exoplanets initially, with additional time through the GO program. Note that Version 2 and Version 3 differ drastically in the "other" science that they can do, but they differ only modestly in the exoplanet science:

- Version 2: in 33 percent of the mission:
    — 92 stars searched to 1.5 $M_\oplus$ in the middle of the HZ , or
    — 55 stars searched to 1.0 $M_\oplus$ in the middle of the HZ.

- Version 3: in 57 percent of the mission:
    — 60 stars searched to 1.0 $M_\oplus$ at the inner edge of the HZ (the ExoPTF recommendation).

Since the intent of the ExoPTF recommendation can be met using about half of the time devoted to science, rather than most of it, it seems likely that an open AO for science time would likely be assigned closer to DRM Version 2 than to Version 3.

Finally, it is worth noting that observatories always exhaust the available observing time long before all viable targets can be observed. This is inherent in the exploratory nature of astronomical observatories. A five-year SIM Lite science program, as laid out in this book, would be an outstanding achievement for this entirely new class of space observatory. An extended mission beyond five years is obviously attractive. Part I of this book showed the power of astrometry to search for exoplanets; an extended mission allows the target list to be broadened — both to more stars, but also for more comprehensive studies of the constituents of the most interesting multiple-planet systems. Many of the astrophysics topics in this book would benefit from more targets — not just for better statistics, but to understand correlations with physical properties. The precision of proper motion measurements improves rapidly (as $t^{-1.5}$), so many dynamical studies, such as galactic dynamics and dark matter characterization, would benefit strongly from a longer time baseline.

A Design Reference Mission is an exercise in possibility. For a high-precision, flexibly scheduled observatory like SIM Lite, at the forefront of research that uses astrometry as a tool, the actual observing program will be decided close to launch, several years from now. The earlier chapters of this book attempt to provide a comprehensive view of the possible science areas. But it is the opportunities for adapting to newly developing fields, and the opportunities for unexpected discoveries, that make SIM Lite such an exciting mission for the next decade.

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