Science in Medieval Jewish Cultures

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town,
Singapore, São Paulo, Delhi, Tokyo, Mexico City

Cambridge University Press
32 Avenue of the Americas, New York, NY 10013-2473, USA

www.cambridge.org
Information on this title: www.cambridge.org/9781107001459

First published 2011

Printed in the United States of America

A catalog record for this publication is available from the British Library.

Library of Congress Cataloging in Publication data

Science in medieval Jewish cultures / edited by Gad Freudenthal.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-107-00145-9 (hardback)
1. Jewish scientists – History – To 1500. 2. Science, Medieval. 3. Judaism and science – History – To 1500.
I. Freudenthal, Gad.
Q128.S35 2011
508.992′4–dc22 2010037107

ISBN 978-1-107-00145-9 Hardback

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Astronomy among Jews in the Middle Ages

Bernard R. Goldstein

In the Middle Ages Jews were deeply involved in the practice of astronomy and they depended on the Greco-Arabic tradition largely based on Ptolemy's *Almagest* composed in the second century C.E. During the first phase, from about 750 to 1100, contributions by Jews, whether in Hebrew or Arabic, were relatively minor compared with those of their Muslim contemporaries.[1] However, in the second phase, beginning in Spain in the twelfth century, some significant works were translated from Arabic into Hebrew and others were summarized. In addition to the dominant Ptolemaic tradition, Jews had access to an astronomical tradition exemplified in Arabic by the tables of al-Khwārizmī (d. ca. 840) that ultimately derived from Hindu sources. Translations from Arabic into Hebrew continued in the thirteenth and fourteenth centuries and, by the end of the thirteenth century, enough material was available in Hebrew for Jews who did not know Arabic to compose original treatises that were more advanced than an introductory work. In addition to those writing in Arabic and in Hebrew, there was an important group under the patronage of Alfonso X, King of Castile (reigned 1252–84), that produced treatises in Castilian. The fourteenth century marks the third phase in which Jews made their most original contributions to astronomy, and this phase continued in the fifteenth century when Jews still excelled in this discipline by the standards of the day. In geographical terms, interest in astronomy can be found in nearly all Jewish communities, but the works produced in Spain and southern France were the most important.[2]

The evidence for Jewish involvement in astronomy is largely based on literary sources preserved in manuscripts, but there are some artifacts (notably astrolabes) and documents preserved in the Cairo Geniza that are now dispersed in various libraries. Other evidence comes from such community decisions as the ban on philosophy decreed in 1305 in Barcelona from which the study of astronomy was specifically excluded. The ban (or *ḥerem*) reads in part as follows:

From this day on and for the next 50 years, no member of our community shall study the "Greek" works on science or metaphysics, either in the original [i.e., in Arabic] or in translation, before he will

[1] See Bernard R. Goldstein, "Astronomy and the Jewish Community in Early Islam," *Aleph* 1 (2001): 17–57.

[2] Gad Freudenthal, "Science in the Medieval Jewish Culture of Southern France," *History of Science* 33 (1995): 23–58; Bernard R. Goldstein, "Scientific Traditions in Late Medieval Jewish Communities," in Gilbert Dahan, ed., *Les Juifs au regard de l'histoire: Mélanges en l'honneur de M. Bernhard Blumenkranz* (Paris: Picard, 1985), pp. 235–47. See also Y. Tzvi Langermann, "Arabic Writings in Hebrew Manuscripts: A Preliminary Relisting," *Arabic Sciences and Philosophy* 6 (1996): 137–60.

have reached the age of 25. . . . We have exempted from our decree the study of medicine, although it is a natural science, for the Torah has given the physician permission to practice the art of healing.

Even though it is not part of the decree itself, its main protagonist, Rabbi Solomon Ibn Adret, pointed out in a letter that "we have expressly exempted from the scope of the enactment the science of astronomy and all the works of Maimonides."[3] This decree is not known to have had much effect on the subjects studied in the Jewish community subsequent to 1305, but it does tell us that astronomy was held in high esteem at the time.

References to astronomy also appear in poems such as Ibn Gabirol's *Keter malḵut*, where the astronomical information was mostly based on the Arabic text of several chapters in the *Epistles of the Sincere Brethren* (*Rasāʾil Ikhwān al-Ṣafāʾ*); in a poem by Moses Ibn Ezra; and in two poems by Levi ben Gerson in praise of the instrument he invented, generally called the cross-staff (but which Levi referred to simply as the staff).[4] Of course, astronomical discussions also abound in medieval philosophical works.[5] Here, however, it is important to distinguish astronomical issues from cosmological concerns.

The main goal of medieval astronomers was to determine by computation the positions of the planets (including the Sun and the Moon) at any given time in the past or the future (there is no difference between past and future in this context) as well as the times of lunar and solar eclipses and their magnitudes. Generally, these computations depended on sets of tables constructed for this purpose, and these tables, in turn, were based on geometrical models for planetary motion. Often the tables were accompanied by instructions for their use without describing how their entries were determined. In some notable instances, however, there was considerable discussion of the underlying models and the observations that justified their parameters, in the style of Ptolemy's *Almagest*. Ptolemy wrote in Greek, and his magnum opus was translated into Arabic (and revised) several times, and then from Arabic into Hebrew by Jacob Anatoli (thirteenth century). Cosmology was not considered by Ptolemy in that book, but he presented his views in the *Planetary Hypotheses* (a work that only partially survives in the original Greek) that was translated into Arabic, and then from Arabic into Hebrew by Qalonymos ben Qalonymos (d. after 1328).[6] In this work Ptolemy determined the planetary distances and sizes based on the nesting hypothesis, namely that the orb of a planet (i.e., the spherical shell that encloses it whose center is the center of the Earth) is contiguous with the orb of the planet immediately below it. For example, with this hypothesis the minimum distance of Mercury is equal to the maximum distance of the Moon. Ptolemy's order of the planets according to their distances from the Earth is: Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn (followed by the orb of the fixed stars). This cosmological scheme was criticized by Maimonides in *Guide* Part II, chapter 24, and it was radically revised by Levi ben Gerson (d. 1344) in his lengthy work on astronomy that constitutes Book 5,

[3] Yitzhak Baer, *A History of the Jews in Christian Spain*, 2 vols. (Philadelphia: Jewish Publication Society, 1966), Vol. 1, pp. 301–2.

[4] Raphael Loewe, "Ibn Gabirol's Treatment of Sources in the *Kether Malkhut*," in Siegfried Stein and Raphael Loewe, eds., *Studies in Jewish Religious and Intellectual History presented to Alexander Altmann* (Tuscaloosa: University of Alabama Press, 1979) pp. 183–94; Adena Tanenbaum, "Nine Spheres or Ten? A Medieval Gloss on Moses Ibn Ezra's *Be-shem El Asher Amar*," *Journal of Jewish Studies* 47 (1996): 294–310; Bernard R. Goldstein, *The Astronomy of Levi ben Gerson (1288–1344)* (New York: Springer-Verlag, 1985), pp. 71–2, 157.

[5] For Saadia and Halevi see, e.g., Goldstein, "Astronomy . . . in Early Islam"; Y. Tzvi Langermann, "Saʿadya and the Sciences," in idem, *The Jews and the Sciences in the Middle Ages* (Aldershot: Ashgate, 1999), Essay II. For Maimonides, the literature is vast; but see, e.g., Y. Tzvi Langermann, "Maimonides and Astronomy: Some Further Reflections," in ibid., Essay IV.

[6] Bernard R. Goldstein, *The Arabic Version of Ptolemy's* Planetary Hypotheses (Philadelphia: American Philosophical Society, 1967). The Hebrew version is uniquely preserved in MS Paris, BNF Héb. 1028. On the life of Qalonymos ben Qalonymos, see Ernest Renan and Adolphe Neubauer, "Les écrivains juifs français du XIV^{e} siècle," *Histoire Littéraire de la France* 31 (1893): 351–789, on pp. 417–24; repr. Westmead: Gregg, 1969.

Part 1, of his *Wars of the Lord*. However, most medieval treatises on astronomy by Jews (and others) omitted discussion of cosmological issues.

In terms of subject matter, Jewish scholars wrote on the whole range of topics treated by medieval astronomers and compiled tables for them: chronology and timekeeping, trigonometry, lunar and solar motion, planetary motion, star lists, and so on. Chronology, that is, dealing with different calendars and how to convert dates from one to another, was often discussed by medieval astronomers, although there were no ancient precedents available to them. Timekeeping, that is, finding the time of day or night by means of astronomical observations, was another concern. We tend to think of trigonometry as a branch of mathematics, but in the Middle Ages it was part of astronomy. The idea for tabulating the sines of angles had come from India to the Islamic world in the late eighth century and largely replaced the table of chords employed by Ptolemy for solving problems in plane and spherical trigonometry.

Lunar and solar motion received a lot of attention in treatises by Jews, and often astronomical tables in Hebrew are restricted to these motions to the exclusion of the planets. However, this may be misleading; for example, Immanuel Bonfils of Tarascon (mid-fourteenth century) compiled two sets of tables, one called *The Six Wings* for lunar and solar motion, and another for the motions of all the planets.[7] Special attention was devoted to lunar and solar eclipses, and tables were arranged for computing their times and magnitudes. Thus, Jacob ben David Bonjorn (also known as Jacob Poʿel; ca. 1360) compiled tables for true conjunctions and oppositions of the Sun with the Moon, as well as for solar and lunar eclipses, computed for the latitude of Perpignan. His tables are based on a thirty-one-year cycle and depend on Levi ben Gerson's tables.[8] Another variety of astronomical table is an almanac that gives planetary positions for specific dates, as opposed to auxiliary tables that may be used to compute positions for arbitrary dates. Noteworthy in this category is the almanac of Jacob ben Maḵir (also known as Prophatius Judaeus), who flourished from 1263 to 1300. This almanac was translated into Latin and consulted by the poet Dante (d. 1321), among others; it was printed in 1908 as Dante's *Almanac* because the editors were interested in Dante rather than in Jacob ben Maḵir, and they used Dante's own copy.[9] Star lists are sometimes short (with 20 to 40 bright stars), and sometimes long (with the 1,028 stars listed by Ptolemy in the *Almagest*). Each entry in such lists includes the star's name, its coordinates (celestial longitude and latitude), its magnitude (understood as its rank in size but, in fact, as we now know, magnitude is a measure of its rank in brightness), and occasionally other data. The coordinates are generally based on previous lists with no appeal to direct observation. The coordinate for celestial longitude of each star was usually updated to the current year by a fixed rule that applied to all the stars in the list, whereas the coordinate for celestial latitude remained unchanged because it does not vary with time.

Jews also described scientific instruments, some of which they had invented or modified. The most commonly described instrument in the Middle Ages was the astrolabe; in addition

7 For Bonfils, see Bernard R. Goldstein, "The Role of Science in the Jewish Community in Fourteenth Century France," *Annals of the New York Academy of Sciences* 314 (1978): 39–49, on pp. 46–7; José Chabás and Bernard R. Goldstein, *Astronomy in the Peninsula: Abraham Zacut and the Transition from Manuscript to Print* (Philadelphia: American Philosophical Society, 2000), pp. 108–9; David A. King and Julio Samsó, with a contribution by Bernard R. Goldstein, "Astronomical Handbooks and Tables from the Islamic World (750–1900): An Interim Report," *Suhayl* 2 (2001): 9–105, on p. 67; Peter Solon, "The Six Wings of Immanuel Bonfils and Michael Chrysokokkes," *Centaurus* 15 (1970): 1–20.

8 See José Chabás, "The Astronomical Tables of Jacob ben David Bonjorn," *Archive for History of Exact Sciences* 42 (1991): 279–314.

9 Giuseppe Boffito and Camillo Melzi d'Eril, *Almanach Dantis Aligherii sive Profhacii Judaei Montispessulani Almanach perpetuum* (Florence: Olschki, 1908).

to treatises, there are five extant examples inscribed in Hebrew characters.[10] An astrolabe has a front and back. The front displays a projection of the sky that allows for easy transformation of coordinates from one system to another, for example, from coordinates with respect to the local horizon to coordinates with respect to the ecliptic (the apparent path of the Sun in the sky), which were generally used for planetary positions. It may also be used to convert an observed position of the Sun or a star with respect to the local horizon to the time before or after noon or midnight. In this way the astrolabe functions as an analog computer, eliminating the need for extensive trigonometric computations. The back serves a number of purposes, including taking observations of the Sun during the day or of stars at night, but there are very few extant records of such observations. It is noteworthy that Levi ben Gerson described modifications of the astrolabe to improve its accuracy and reliability for making observations. One such improvement was the invention of a transversal scale that permitted very fine graduations of an arc.[11] A modified version of the astrolabe, known as the "new quadrant" or "quadrant of Israel," was invented and described by Jacob ben Maḵir.[12] Furthermore, Levi ben Gerson invented several new observational instruments, including the aforementioned cross-staff, that were still being used by European astronomers in the seventeenth century.[13]

Astrology is often seen as indistinguishable from astronomy as it was practiced in the Middle Ages. However, it is clear that although some astronomers accepted astrology and were practitioners of this art, others opposed it, and still others simply ignored it. Each case deserves separate treatment, and sweeping generalizations are inappropriate. For details, another essay in this volume may be consulted.[14]

SPAIN

The astronomical tradition in Hebrew began in Spain in the twelfth century, and it is closely associated with Abraham Bar Ḥiyya and Abraham Ibn Ezra.

Abraham Bar Ḥiyya of Barcelona and Abraham Ibn Ezra brought Arabic astronomy to the attention of members of the Jewish community who were not literate in Arabic. Among other things, this required the formation of a new technical vocabulary. Bar Ḥiyya tended to use Arabic terms transliterated into Hebrew characters, whereas Ibn Ezra tended to give new meanings to biblical terms. For example, Bar Ḥiyya adopted the Arabic *markaz* (center), which became Hebrew *merkaz,* whereas for this purpose Ibn Ezra recycled the biblical term *muṣaq,* giving it an entirely new meaning. Bar Ḥiyya was heavily reliant on the *zij* (a set of astronomical tables with instructions or canons) by al-Battānī (d. 929), whose work was widely used in Spain, whereas Ibn Ezra appealed both to al-Battānī, who represented the Greek tradition, and to al-Khwārizmī, who represented the Indian tradition. Both astronomical traditions flourished in Islamic Spain. Bar Ḥiyya's astronomical tables in Hebrew were largely drawn from those of al-Battānī, although Bar Ḥiyya arranged them for the Jewish calendar with its nineteen-year cycle, rather than for the calendars used by al-Battānī. Among the many astronomical works by Ibn Ezra is a translation into Hebrew of a lost Arabic commentary by Ibn al-Muthannā (tenth century) on the astronomical tables of al-Khwārizmī. Nonetheless, from the point of view of technical astronomy, neither Bar Ḥiyya

10 Bernard R. Goldstein, "The Hebrew Astrolabe in the Adler Planetarium," *Journal of Near Eastern Studies* 35 (1976): 251–60, on p. 251 n. 1.

11 Goldstein, *Astronomy of Levi ben Gerson,* pp. 164–70.

12 Moritz Steinschneider, *Mathematik bei den Juden,* 2nd ed. (Hildesheim: Georg Olms, 1964), pp. 111–13; John D. North, *Richard of Wallingford,* 3 vols. (Oxford: Clarendon Press, 1976), Vol. 2, p. 184, and Vol. 3, plate XI.

13 See John J. Roche, "The Radius Astronomicus in England," *Annals of Science* 38 (1981): 1–32.

14 Shlomo Sela, "Astrology in Medieval Jewish Thought," elsewhere in this volume.

nor Ibn Ezra was responsible for any innovations; rather, they transmitted knowledge of the traditions of Muslim Spain at a relatively elementary level.[15]

Both Bar Ḥiyya and Ibn Ezra compiled lists of bright stars based on Arabic sources that ultimately depended on Ptolemy's *Almagest*. Because it was assumed that the fixed stars all move together slowly about the poles of the celestial ecliptic (which is true to a first approximation), their positions depended on the date. In the case of Bar Ḥiyya the list of positions of some twenty-eight stars, with names in both Hebrew and Arabic, is given for 1104 CE, and he relied on the astronomical work of al-Battānī. Ibn Ezra has two versions of his list, one for 1146 C.E. with thirty-six stars, and the other for 1148 C.E. with twenty-three stars. This star list is related to an Arabic text by Ibn al-Zarqāllu, a prominent Muslim astronomer who lived in Spain in the eleventh century.[16]

Isaac ben Sid, a member of the team of astronomers under the patronage of Alfonso X of Castile, is best known for the Castilian version of the Alfonsine Tables (ca. 1270) for which he was the author (together with Judah ben Moses ha-Cohen). This team comprised a number of Jews along with some Christians, and the bulk of the work involved Jewish participants. Ben Sid's surviving works in Castilian are extensive, and he composed treatises on several scientific instruments. The Alfonsine Tables were translated into Latin and diffused from Paris, beginning in the 1320s, and they became the most widely consulted set of astronomical tables in the Latin West for well over two centuries. There are relatively few references to Ben Sid in Hebrew astronomical works, but he is mentioned by Judah ben Asher II (d. 1391) and by Abraham Zacut (d. 1515).[17]

PROVENCE

A great many Jewish astronomers flourished in Provence from the thirteenth to the fifteenth century, among them the translator Samuel ben Judah of Marseilles.[18] He was born in 1294, and his family had lived in Provence for at least 150 years prior to that time. In 1312, at the age of eighteen, he began his studies of philosophy and astronomy under the tutelage of a Jewish scholar at Salon-de-Provence. As we learn from a work he completed in 1324, Samuel traveled to Spain where he pursued his translational activities. But in 1329 he was back in Provence in Tarascon, and in 1330–1 he completed his first independent treatise, a commentary on the first three books of Ptolemy's *Almagest*. He then turned his attention to Arabic astronomical works produced in Spain, particularly the *Reparation of the Almagest* (*Iṣlāḥ al-Majisṭī*) by Jābir Ibn Aflaḥ (twelfth century). To locate a copy of the Arabic text, Samuel and his brother first went to Trinquetaille, near Arles. However, they had access to the text for only two days, and they returned to Tarascon with a very incomplete copy. Later, in Aix-en-Provence, Samuel discovered a previous Hebrew translation of Jābir's text by Jacob ben Maḵir, but he decided it was seriously deficient. Samuel then got a copy of the Arabic text he had seen a few years earlier in Trinquetaille; he completed his revision of the previous Hebrew translation in 1335. Jābir was a severe critic of Ptolemy, and his treatise was

[15] For Bar Ḥiyya, see, e.g., Y. Tzvi Langermann, "Science in the Jewish Communities of the Iberian Peninsula: An Interim Report," in idem, *The Jews and the Sciences*, Essay I, on pp. 10–16. For Ibn Ezra, see, e.g., Bernard R. Goldstein, "Arabic Astronomy and Astrology in the Works of Abraham Ibn Ezra," *Arabic Sciences and Philosophy* 6 (1996): 9–21; and Shlomo Sela, *Abraham Ibn Ezra and the Rise of Medieval Hebrew Science* (Leiden: Brill, 2003).

[16] Bernard R. Goldstein, "Star Lists in Hebrew," *Centaurus* 28 (1985): 185–208.

[17] José Chabás and Bernard R. Goldstein, *The Alfonsine Tables of Toledo* (Dordrecht: Kluwer, 2003), pp. 4, 138, 226. For Judah ben Asher II, see Chabás and Goldstein, *Abraham Zacut*, pp. 49–50.

[18] Lawrence V. Berman, "Greek in Hebrew: Samuel ben Judah of Marseilles, Fourteenth-Century Philosopher and Translator," in Alexander Altmann, ed., *Jewish Medieval and Renaissance Studies* (Cambridge, MA: Harvard University Press, 1967), pp. 289–320.

influential in the original Arabic as well as in Latin and in Hebrew translations (the Latin translation was printed in Nuremberg in 1534). Some of the works translated by Samuel do not survive in the original Arabic and thus are of great importance for reconstructing several key episodes in the history of astronomy. For example, he translated a treatise on twilight by the Spanish-Muslim astronomer Ibn Muʿādh (eleventh century) in which the height of the atmosphere was estimated to be about 50 miles (in units in which the circumference of the Earth was taken to be 24,000 miles), a value that was widely accepted until the seventeenth century. Samuel's last dated activity was in 1340, and he probably died shortly thereafter.[19]

Let us next consider the achievements of Levi ben Gerson of Orange, the most talented Jewish astronomer in the Middle Ages. His family name in Latin is given as "de Balneolis," but research in local archives suggests that, whereas an ancestor resided in Bagnols-sur-Cèze in Languedoc, Levi was probably born in Orange. Little is known about his life except that he occasionally traveled to nearby Avignon, for he says explicitly that some of his astronomical observations were made there. He was a prolific writer who composed many biblical commentaries and several philosophical works. For our purposes, though, his treatises on astronomy are the most important. Curiously, his main astronomical work was incorporated into a long philosophical work as Book 5, Part 1, of his *Wars of the Lord*. However, his *Astronomy* is an independent text that is extant in manuscripts distinct from those that survive of his philosophical work. It is divided into 136 chapters that fill over 200 folios in manuscript – and only a small portion of this work has been published or translated into a modern language. There was also a medieval Latin translation made with Levi's participation by a certain cleric, Peter of Alessandria, Italy, who is otherwise unknown. In 1342 a short version of the Latin text was dedicated to Pope Clement VI, who resided in Avignon. Levi's *Astronomy* had not been completed at the time of his death, for there are internal indications of revisions, and in all surviving manuscripts we find blank spaces – and even a few missing chapters – where he may have intended to insert further revisions.[20]

As already mentioned, Ptolemy's *Almagest* was the foundation for most of medieval astronomy, and Levi was certainly dependent on Ptolemy. Nevertheless, Levi organized his *Astronomy* in a completely new fashion, and he set his goals in a philosophical context. After some preliminary matters, Levi turned to trigonometry and the determination of entries in a table for the sines of angles, which were standard topics in medieval astronomy. However, the next topic, astronomical instruments, was placed more prominently than in other comparable texts of the time. In these chapters he discussed the cross-staff that he claimed to have invented, the camera obscura, and the astrolabe. Significantly, Levi gave a correct explanation for the workings of the camera obscura that eluded astronomers, ignorant of Levi's work, until Kepler arrived at essentially the same explanation at the beginning of the seventeenth century.

Levi then discussed the range of phenomena that an astronomical theory must take into consideration. Unlike Ptolemy and his followers, whose theories only depended on positional data, Levi said that physical data also have to be taken into account. In particular, he reported observations of the variation in the brightness of Mars at successive oppositions (when Mars come closest to the Earth), and he compared its brightness with that of Saturn. Before the invention of the telescope, size and brightness of planets and stars were not

19 Bernard R. Goldstein, "Ibn Muʿâdh's Treatise on Twilight and the Height of the Atmosphere," *Archive for History of Exact Sciences* 17 (1977): 97–118; A. Mark Smith and Bernard R. Goldstein, "The Medieval Hebrew and Italian Versions of Ibn Muʿâdh's 'On Twilight and the Rising of Clouds,'" *Nuncius* 8 (1993): 611–43.

20 Bernard R. Goldstein, *Levi ben Gerson's Astronomical Tables* (Hamden, CT: Archon Books, 1974), pp. 74–83; idem, *Astronomy of Levi ben Gerson*; José Luis Mancha, "The Latin Translation of Levi ben Gerson's *Astronomy*," in Gad Freudenthal, ed., *Studies on Gersonides: A Fourteenth-Century Jewish Philosopher-Scientist* (Leiden: Brill, 1992), pp. 21–46.

distinguished, and Levi (together with all medieval astronomers) assumed that a brighter celestial object had a greater angular size. As far as I can tell, no one before Kepler, other than Levi, unambiguously mentions this variation at opposition, although the difference in the size or brightness of Mars at apogee and perigee was occasionally noted. Levi also treated the phases of Venus in detail and argued that they ought to be visible if Venus received its light from the Sun. But, in the absence of such phases, he concluded that Venus must be self-luminous.[21] Again, it was only with the telescope that Galileo was able to discern phases of Venus for the first time. In the case of the Moon, Levi took issue with Ptolemy's account of the lunar distances that follow from his final lunar model, for it required that the Moon be twice as large in diameter at quadrature (half-Moon phase) than at opposition (full Moon), contrary to what is observed. Although one would expect this comment to be widespread, I am not aware of anyone before Levi making it. Later in the fourteenth century the same criticism of Ptolemy was voiced by Ibn al-Shāṭir, a Muslim astronomer in Damascus, and in the fifteenth century it was mentioned by Regiomontanus. Levi also appealed to the spots on the Moon (commonly called the Man in the Moon) to argue that we only see one lunar face, from which he concluded that an epicyclic model for lunar motion is impossible because it implies we should see both lunar faces (i.e., the front and the back of the Moon). Here again, Levi departed from Ptolemy on the basis of observation, arguing that, although the eccentric and epicyclic models are equivalent mathematically, they have different physical consequences.[22]

In his long discussion of alternative models for planetary motion Levi considered various arrangements of the three centers that Ptolemy used in his models, namely the Earth, the center of the deferent (a circle on which the center of the epicycle is located), and the equant (about which uniform motion takes place). Note that the path of a planet in three dimensions was not considered before Kepler (who coined the term "orbit" for this path), and Levi was no exception in this respect. Levi then appealed to the principle of the uniformity of nature to argue that the absence of an epicycle for the Moon means that there are no epicycles for the planets either. By way of contrast, Ptolemy's planetary models had both eccentric circles and epicycles. Levi constructed several lunar models and produced a table for one of them. The transformation of a geometric model to a table for computing positions without requiring trigonometric solutions of triangles had already been done by Ptolemy for his models, but Levi had to use somewhat different techniques because his model was very different from Ptolemy's. In the case of the five planets, Levi's tables do not survive, and the chapters on planetary models are incomplete.

Levi used his instruments to make precise observations of planetary and lunar positions. In the case of the Moon he compared various models to see how well they accounted for these observed positions, and he argued that his new lunar model was significantly more successful than Ptolemy's. It should be emphasized that Levi compared his own observations with various models whereas in the Middle Ages it was much more common to determine the success of an alternative to Ptolemy's models by assessing how well it accounted for Ptolemy's observations (rather than those made by the author). This means that Levi had greater confidence in his own observations than was generally true for his contemporaries.

[21] Bernard R. Goldstein, "Levi ben Gerson and the Brightness of Mars," *Journal for the History of Astronomy* 27 (1996): 297–300; idem, "The Pre-Telescopic Treatment of the Phases and Apparent Size of Venus," *Journal for the History of Astronomy* 27 (1996): 1–12.

[22] Bernard R. Goldstein, "The Physical Astronomy of Levi ben Gerson," *Perspectives on Science* 5 (1997): 1–30; Alan Gabbey, "Innovation and Continuity in the History of Astronomy: The Case of the Rotating Moon," in Peter Barker and Roger Ariew, eds., *Revolution and Continuity: Essays in the History and Philosophy of Early Modern Science* (Washington, D.C.: Catholic University of America Press, 1991), pp. 95–129, on pp. 112–20.

Levi records over eighty specifically dated astronomical observations, many more than any of his contemporaries (Christian, Muslim, or Jewish).[23]

Levi did not casually depart from Ptolemy's models:

When deciding to dissent from the teachings of the ancients, one should do so with extreme care and scrutiny, deviating from these teachings as little as possible. This is appropriate because the ancients were lovers of truth and endeavored to approach it as closely as possible even when their principles prevented them from reaching it entirely. . . . Therefore we first tried to solve some of the difficulties raised against Ptolemy by our predecessors with respect to his postulates concerning eccentric spheres and epicycles, seeking to find observational evidence to establish his hypotheses. . . . When we investigated this matter for the Moon and found that the model could not possibly be as Ptolemy postulated, we took pains to investigate alternative possibilities for the models of the celestial bodies until we discovered a model according to which the motions of these bodies conform to observational evidence.[24]

Levi's views on cosmic dimensions differed significantly from those of his predecessors and contemporaries. Although he accepted Ptolemy's nesting hypothesis, he interpreted it in an unusual way, invoking a principle taken from the motion of fluids. For Ptolemy, adjacent planetary orbs are treated as contiguous with no empty space between them. In contrast, according to Levi, the planetary orbs are separated by a fluid that has the property of moving with the motion of the orb below it at its lower boundary. The motion of layers in the fluid then diminishes according to their distance from the center of the Earth until a layer is reached where it is zero, and then the motion of subsequent layers begins to increase until at its upper boundary it reaches the motion of the orb above it. The thickness of the fluid layer between each pair of planetary orbs is determined by a procedure involving successive approximations, and this led Levi to increase the size of the universe considerably from Ptolemy's 20,000 terrestrial radii for the distance from the Earth to the fixed stars. [25]

ITALY

There are also indications that astronomy attracted the attention of Jews in Italy. For example, a manuscript in Florence contains a Hebrew translation of an introductory work in Arabic by al-Kharaqī (d. 1138/9), *Kitāb al-tabṣīra*, by Nathan ha-Meʾati (i.e., Nathan from the city of Cento; thirteenth century).[26] This translator is otherwise known for his medical rather than astronomical interests. The most significant Jewish astronomer in Italy was Mordecai Finzi, who lived in Mantua in the fifteenth century. His translations from Latin include a set of astronomical tables by an Englishman, William Batecombe (fourteenth century), originally for the city of Oxford. In the middle of the fifteenth century Bartolomeo Manfredi of Mantua composed a treatise in Italian, only extant in a Hebrew translation by Finzi, that describes a geared instrument called *celidario*. This instrument belongs to the category of

[23] Bernard R. Goldstein, "Medieval Observations of Solar and Lunar Eclipses," *Archives Internationales d'Histoire des Sciences* 29 (1979): 101–56; idem, "A New Set of Fourteenth Century Planetary Observations," *Proceedings of the American Philosophical Society* 132 (1988): 371–99; José Luis Mancha, "Gersonides' Astronomical Work: Chronology and Christian Context," in Colette Sirat, Sara Klein-Braslavy, and Olga Weijers, eds., *Les méthodes de travail de Gersonide et le maniement du savoir chez les scolastiques* (Paris: Vrin, 2003), pp. 39–58, on pp. 55–7.

[24] Goldstein, "Planetary Observations," p. 385. See also Bernard R. Goldstein, "Levi ben Gerson on the Sources of Error in Astronomy," *Aleph* 10 (2010): 211–40.

[25] Bernard R. Goldstein, "Levi ben Gerson's Theory of Planetary Distances," *Centaurus* 29 (1986): 272–313; José Luis Mancha, "Heuristic Reasoning: Approximation Procedures in Levi ben Gerson's Astronomy," *Archive for History of Exact Sciences* 52 (1998): 13–50, on pp. 34–9.

[26] Bernard R. Goldstein, "The Survival of Arabic Astronomy in Hebrew," *Journal for the History of Arabic Science* 3 (1979): 31–9, on p. 31; idem, "Scientific Traditions in Late Medieval Jewish Communities," p. 238.

equatoria, that is, devices for determining planetary positions without recourse to numerical computation. Many such devices were described in Latin in the Middle Ages, but only a few in Hebrew.[27]

In Sicily it seems that the astronomical tradition began with the arrival of Isaac Ibn al-Aḥdab (or al-Ḥadib) from Spain at the end of the fourteenth century. Among his compositions is a set of astronomical tables for the Sun and the Moon called *ʾOraḥ selulah* in which he mentions both Jewish and Muslim predecessors.[28] As a sign of its popularity, Abraham Gascon (Cairo, ca. 1540) wrote a commentary on Ibn al-Aḥdab's set of tables. Ibn al-Aḥdab also composed a treatise on an *equatorium* to represent Ptolemy's planetary models, which begins as follows:

> Finding the true positions of the seven planets [the five planets plus the Sun and the Moon] . . . involves difficulty and effort in the [use of] all the different kinds of tables that have been composed for these purposes that cannot be avoided. . . . Moreover, errors affect the results . . . because of the multitude of operations, sometimes to be added and sometimes to be subtracted. . . . Many have tried to construct instruments to simplify this as was done for the Sun on [the back of] the astrolabe. . . . But these instruments came with lengthy instructions and could only be used with great difficulty. [Such is the case] with the instrument ascribed to al-Zarqāllu, and other [instruments invented] by Christian scholars. . . . In the year 5156 AM [i.e., 1396 CE] in Syracuse on the island of Sicily . . . I invented an instrument that is easy to construct and it is accurate to a degree [of longitude].[29]

It is not known if anyone actually constructed such an instrument according to Ibn al-Aḥdab's instructions that form the bulk of this treatise.

THE LATE PHASE: JUDAH BEN VERGA AND ABRAHAM ZACUT

The vibrant Jewish tradition in astronomy lapsed at the end of the fifteenth century, and no Jewish astronomer from that time until the emancipation met contemporary standards for practitioners of astronomy. There were two outstanding Jewish astronomers in the late fifteenth century in the Iberian peninsula: Judah ben Verga of Lisbon, Portugal, who was active between 1455 and 1475, and Abraham Zacut (1452–1515), who spent his most creative years as an astronomer in Salamanca, Spain – but, after the expulsion from Spain in 1492, he moved to Portugal, and then to North Africa, Jerusalem, and Damascus.

Judah ben Verga's Hebrew treatises have only recently begun to be studied, and none of his astronomical works have been published. He wrote a treatise on an astronomical instrument that he called *ha-keli ha-ʾofqi* (the horizontal instrument), and among the observations he recorded is one he made at Lisbon of an autumnal equinox in 1456. Judah mentioned a number of Jewish predecessors in astronomy, including Abraham Ibn Ezra and Levi ben Gerson. His most important work is a set of astronomical tables, *Ḥuqot šamayim* (Ordinances of the Heavens: cf. Job 38:33), and it has a number of unusual features.[30]

[27] Bernard R. Goldstein, "Descriptions of Astronomical Instruments in Hebrew," in David A. King and George Saliba, eds., *Essays in Honor of E. S. Kennedy* (New York: New York Academy of Sciences,1987), pp. 105–41, on pp. 120–1. On Finzi, see Y. Tzvi Langermann, "The Scientific Writings of Mordekai Finzi," *Italia* (1988): 7–44; repr. in idem, *The Jews and the Sciences*, Essay IX.

[28] Bernard R. Goldstein and José Chabás, "Isaac Ibn al-Ḥadib and Flavius Mithridates: The Diffusion of an Iberian Astronomical Tradition in the Late Middle Ages," *Journal for the History of Astronomy* 37 (2006): 147–72.

[29] Goldstein, "Descriptions of Astronomical Instruments," p. 128.

[30] Bernard R. Goldstein, "The Astronomical Tables of Judah ben Verga," *Suhayl* 2 (2001): 227–89; idem, "Preliminary Remarks on Judah ben Verga's Contributions to Astronomy," pp. 63–90 in Luís Saraiva and Henrique Leitão, eds., *The Practice of Mathematics in Portugal* (Coimbra: Coimbra University Press, 2004); Y. Tzvi Langermann, "Science in the Jewish Communities of the Iberian Peninsula," pp. 19–34.

Zacut's main astronomical work is a *zij* in Hebrew called *ha-Ḥibbur ha-gadol* (The Great Composition). Despite claims in secondary sources that Zacut taught at the University of Salamanca, this has no basis in fact and derives from the dedication to an unnamed bishop of Salamanca in the Latin version of the 1496 edition of the *Almanach Perpetuum* that includes the astronomical tables compiled by Zacut in his *Ḥibbur*.[31] This dedication was simply lifted almost verbatim from a dedication by Regiomontanus (d. 1476) to a bishop in Hungary in a work published in 1490 (and there is no Hebrew version of it). It is now clear that Zacut had nothing to do with the edition of 1496 and never refers to it in his subsequent writings. In contrast, the *Ḥibbur* is clearly addressed to a Jewish audience with references to Maimonides and the Talmud that are missing in the published Latin text. Indeed, Zacut's canons to his *Ḥibbur* bear little resemblance to those in the *Almanach Perpetuum*. In particular, Zacut refers mainly to Jewish astronomers such as Levi ben Gerson, Jacob ben David Bonjorn, Judah ben Verga, and Judah ben Asher II of Burgos, the great-grandson of Asher ben Yehiel (d. 1328), a refugee from Cologne who became the chief rabbi of Toledo. Judah ben Asher II has often been confused with Judah, the son of Asher ben Yehiel, who died in 1349. An astronomical treatise by Judah ben Asher II has only recently been identified in a Hebrew manuscript at the Vatican.[32]

Among Zacut's innovations are some astronomical tables with base-30 notation for numbers rather than the usual base-60 notation used by astronomers (including Zacut himself) or base-10 notation that is familiar to us today. Zacut argued for consistency because the zodiac is divided into twelve equal signs of 30°, but I know of no one after him who accepted this notation.[33] His tables are mostly in the form of almanacs, that is, planetary positions for specific dates, beginning in 1473. The positions themselves were computed accurately with the Parisian version of the Alfonsine Tables. Although he generally used the Christian calendar, there are a few tables in the *Ḥibbur* based on the Jewish calendar with years counted from the Creation. However, in Jerusalem, where he lived in 1513, Zacut constructed a new set of tables for the Jewish calendar that is only extant in fragments. In the sixteenth and seventeenth centuries Zacut was considered an authority on astronomy in the Jewish communities of Palestine, Syria, and Iraq.[34] Zacut has often been associated with the voyages of discovery undertaken by Portuguese sailors, but there is no contemporary documentation to support these claims that only go back to the mid-sixteenth century. In fact, Zacut made very few astronomical observations (they can be counted on the fingers of one hand!), and he had little to say about astronomical instruments in any of his treatises. It is difficult to imagine that an experienced navigator would consult someone who had lived far from the sea with no specific expert knowledge to impart.[35]

In a reversal of the usual pattern, the Spanish version of the *Almanach Perpetuum* (with Zacut's tables) was translated into Arabic in North Africa in the early seventeenth century by Aḥmad b. Qāsim al-Ḥajarī (d. after 1641) who had lived in Seville before arriving in Morocco around 1600. This Arabic version survives in a number of manuscripts in European libraries as well as in Morocco and Egypt. Moreover, Moses Galiano (or Galeano), who was active in

[31] For Zacut's relations with Christian scholars, see José Chabás, "Interactions Between Jewish and Christian Astronomers in the Iberian Peninsula," elsewhere in this volume.

[32] Bernard R. Goldstein, "Astronomy in the Medieval Spanish Jewish Community," in Lodi Nauta and Arjo Vanderjagt, eds., *Between Demonstration and Imagination: Essays in the History of Science and Philosophy Presented to John D. North* (Leiden: Brill, 1999), pp. 225–41, on pp. 235–6.

[33] Bernard R. Goldstein, "Abraham Zacut and the Medieval Hebrew Astronomical Tradition," *Journal for the History of Astronomy* 29 (1998): 177–86, on p. 181.

[34] Bernard R. Goldstein, "The Hebrew Astronomical Tradition: New Sources," *Isis* 72 (1981): 237–51, on pp. 245–6.

[35] Chabás and Goldstein, *Abraham Zacut*, pp. 9–11.

the Jewish community of Istanbul, produced an Arabic adaptation of the *Almanach Perpetuum* in 1506/7.[36]

CONCLUDING REMARKS

It is well to consider a few issues for further research in addition to the obvious need for editions of key texts with translation and commentary. Allusions to astronomy can be found in many literary genres, and they should be explored. For example, there is no adequate survey of scientific discussions that appear in halakhic (legal) contexts. Moreover, the Karaites did not accept the Rabbanite rules for computing the calendar and insisted on direct observation. Their contributions to astronomy remain to be elucidated.[37] The Karaite scholar Caleb Afendopolo (1464?–1525) was the owner of the oldest extant manuscript of Levi ben Gerson's *Astronomy*, and he himself executed a copy of the Hebrew version of Jābir Ibn Aflaḥ's *Restoration of Astronomy* (both preserved in the Bibliothèque nationale de France).[38] In fact, Caleb was an astronomer in his own right but, as far as I know, his scientific works have attracted little attention.[39] The kabbalists are another group whose references to scientific issues are not well documented in the secondary literature. For example, Ḥayyim Vital, a noted kabbalist (d. 1620), wrote an introduction to astronomy that is thoroughly medieval in content (he cites Zacut among others); it was printed (in part) in Jerusalem in 1866 for the traditional Jewish community there.[40] Moreover, astronomical (and astrological) considerations sometimes entered into Messianic speculations, and this was the case for Abraham Zacut, among others. Already in the twelfth century Maimonides attacked such speculation in his *Epistle to Yemen* (without mentioning any specific authors except for Saadia), and earlier in the twelfth century Abraham Bar Ḥiyya had written on the End of Days according to the Book of Daniel as well as according to astrological (and astronomical) theory.[41]

In sum, it should be stressed that interest in astronomy, by intellectuals with a variety of commitments, is in evidence in virtually all medieval Jewish communities.

[36] Ibid., pp. 170–1; Julio Samsó, "Abraham Zacut and José Vizinho's *Almanach Perpetuum* in Arabic (16th–19th C.)," *Centaurus* 46 (2004): 82–97; Y. Tzvi Langermann, "A Compendium of Renaissance Science: *Taʿalumot ḥoḵmah* by Moses Galeano," *Aleph* 7 (2007): 285–318.

[37] For an overview, see Daniel Lasker, "Science in the Karaite Communities," in this volume.

[38] Goldstein, *Tables of Levi ben Gerson*, pp. 74–5.

[39] See, e.g., Caleb Afendopolo, *Sefer Miḵlal yofi*, ed. Yosef Elgamil (Ashdod: Meḵon tif'eret Yosef, 2002).

[40] Goldstein, "New Sources," p. 245.

[41] Bernard R. Goldstein and David Pingree, "Horoscopes from the Cairo Geniza," *Journal of Near Eastern Studies* 36 (1977): 113–44, on pp. 114–15; idem, *Levi ben Gerson's Prognostication for the Conjunction of 1345* (Philadelphia: American Philosophical Society, 1990); Chabás and Goldstein, *Abraham Zacut*, pp. 15, 173–4.