INSTRUCTOR SOLUTIONS MANUAL

Foundations of Astrophysics

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Preface

This manual provides complete solutions to the end-of-chapter exercises for *Foundations of Astrophysics* by Barbara Ryden and Bradley M. Peterson, a first course in astrophysics intended primarily for second-year majors in the physical sciences. SI units, augmented when necessary by various units peculiar to astronomy, are used throughout. In the written solutions, units are given whenever they may not be obvious.

Although most of the problems in this book have been heavily field-tested over the years, no doubt some errors, both typographical and conceptual, have eluded our scrutiny. The authors would be pleased to learn of any errors in the textbook or this solutions manual.

This solutions manual is intended to be an evolving document since it is expected to be made available only to instructors via a secure website. It will therefore be updated regularly by the authors, and the revision history will be recorded at the end. Also at the end of this manual will be a list of known errors found in the textbook itself.

We thank Catherine J. Grier for her help in proofreading this manual.

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Chapter 1

Early Astronomy

1.1. The Polynesian inhabitants of the Pacific reportedly held festivals whenever the Sun was at the zenith at local noon. How many times per year was such a festival held? At what time(s) of year was the festival held on Tahiti? At what time(s) of year was it held on Oahu? [Hints: any reputable world atlas will give you the latitude of Tahiti and Oahu. You may also find the information in Figure 1.13 to be useful.]

The latitude of Tahiti $= -17^{\circ}\,37'$. The Sun crosses this declination on approximately 2 February and 1 November.

The latitude of Oahu is $+21^{\circ}\,28'$ and the Sun crosses this declination on approximately May 29 and July 16.

We note in passing that both Tahiti and Oahu extend about $25'$ of latitude in the north–south direction.

1.2. For what range of latitudes are all the stars of the Big Dipper circumpolar? Use the stars in the following table:

Star	Right Ascension	Declination
Alkaid	$13^{\mathrm{h}}48^{\mathrm{m}}$	$+49^{\circ}19'$
Mizar	$13^{\mathrm{h}}24^{\mathrm{m}}$	$+54^{\circ}56'$
Alioth	$12^{\mathrm{h}}54^{\mathrm{m}}$	$+55^{\circ}58'$
Megrez	$12^{\mathrm{h}}15^{\mathrm{m}}$	$+57^{\circ}02'$
Phecda	$11^{\mathrm{h}}54^{\mathrm{m}}$	$+53^{\circ}42'$
Merak	$11^{\mathrm{h}}02^{\mathrm{m}}$	$+56^{\circ}23'$
Dubhe	$11^{\mathrm{h}}04^{\mathrm{m}}$	$+61^{\circ}45'$

For all the stars to be circumpolar, the southernmost star (Alkaid) must be above the horizon at lower transit, as shown in Figure 1.1. Thus the elevation of the North Celestial Pole must be equal to the angle between Alkaid and the

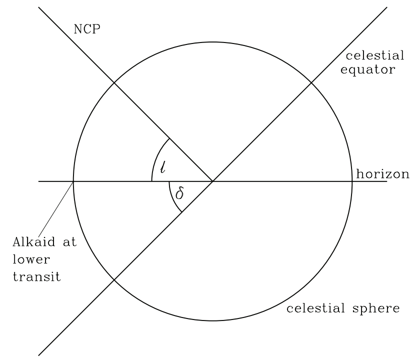

Figure 1.1: Southernmost latitude from which all the stars of the Big Dipper will be circumpolar.

NCP; the elevation is $\ell = 90^o - \delta_{\rm Alkaid} = 90^o - 49^o 19' = 40^o 41'$. Only for observers at this latitude or higher will all the Big Dipper stars be circumpolar.

What is the southernmost latitude from which all of the stars of the Big Dipper can be seen?

For all the stars to be visible, the northernmost star (Dubhe) must be at the horizon at upper transit, as shown in Figure 1.2. In other words, the NCP is below the horizon by an angle equal to the separation between the NCP and Dubhe, i.e., $90^o - \delta_{\rm Dubhe} = \ell$. Thus $\ell = \delta_{\rm Dubhe} - 90^o = 61^o 45' - 90^o = -28^o 15'$. Only observers at or north of latitude $-28^o 15'$ can see all the stars of the Big Dipper.

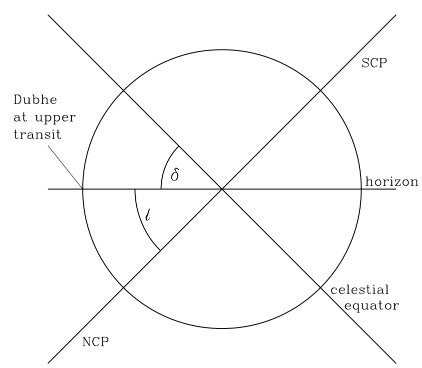

Figure 1.2: Southernmost latitude from which all the stars of the Big Dipper can be seen.

For what range of latitudes are none of the stars of the Big Dipper ever seen above the horizon?

For all of the stars to be below the horizon, the southernmost star must be on the horizon at upper transit, as shown in Figure 1.3. In other words, the NCP must be below the horizon by an angle equal to the distance between the NCP and Alkaid, i.e., $90^o - \delta_{\rm Alkaid} = -\ell$ or $\ell = \delta_{\rm Alkaid} - 90^o = 49^o19' - 90^o = -40^o41'$. Observers south of this latitude cannot observe any of the stars of the Big Dipper.

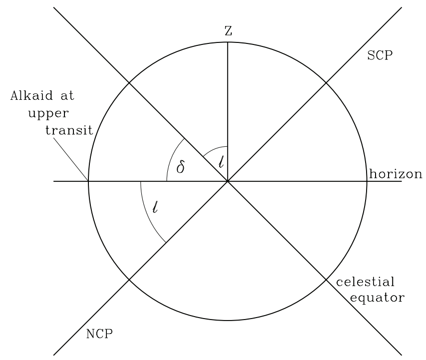

Figure 1.3: Northernmost latitude from which none of the stars of the Big Dipper can be seen.

1.3. Columbus, Ohio, is in the Eastern Time Zone, for which the civil time is equal to the mean solar time along the 75° W meridian of longitude.
(a) Ignoring daylight saving time for the moment, are there any days of the year when civil noon (as shown by a clock) is the same as apparent local noon (as shown by the Sun) in the city of Columbus? If so, what day or days are they?

The longitude of Columbus is $82^o59'$ west. The zone time is set to longitude 75^o, so Columbus is behind the zone time by

$$82^o59' - 75^o = 7^o59'\left(\frac{12^{\rm h}}{180^o}\right) = 0.53^{\rm h}\left(\frac{60^{\rm m}}{1^{\rm h}}\right) = 31.9^{\rm m}.$$

Since the amplitude of the Equation of Time is only $\sim 18^{\rm m}$, the Sun *never* transits the meridian at local noon in Columbus, it always transits $\sim 14^{\rm m}$ to $50^{\rm m}$ after noon, zone time.

(b) Daylight savings time advances the clock by one hour from the second Sunday in March to the first Sunday in November ("Spring forward, fall back"). When daylight savings time is in effect, are there

any days of the year when civil noon is the same as apparent local noon in the city of Columbus? If so, what day or days are they?

Since the zone time is advanced an hour, the problem is made worse by daylight savings time. During DST, the Sun crosses the meridian more than an hour after noon, zone time.

1.4. Suppose you've been granted access to a large telescope during the last week in September. One of the two objects you want to observe is in the constellation Virgo; the other is in the constellation Pisces. You only have time to observe one object: which should you choose? Please explain your answer.

The right ascension of Virgo is $\alpha \sim 13^{\mathrm{h}}$ and Pisces is at $\sim 0^{\mathrm{h}}$. The autumnal equinox is the third week of September: since the vernal equinox is $\alpha = 0^{\mathrm{h}}$, the Sun must be at $\alpha \sim 12^{\mathrm{h}}$ at the autumnal equinox. Virgo is thus unobservable, only an hour from the Sun. Pisces, however, will be crossing the meridian at midnight.

1.5. In *The Old Man and the Sea*, Hemingway described the old man lying in his boat off the coast of Cuba, looking up at the sky just after sunset: "It was dark now as it becomes dark quickly after the Sun sets in September. He lay against the worn wood of the bow and rested all that he could. The first stars were out. He did not know the name of Rigel but he saw it and knew soon they would all be out and he would have all his distant friends." Explain what is astronomically incorrect about this passage. [Hint: what are the celestial coordinates of the star Rigel?]

The right ascension of Rigel is $\alpha \sim 6^{\mathrm{h}}$ and its declination is $\delta \sim -8^{\mathrm{o}}$, so it is not circumpolar seen from Cuba. In September, the Sun is at $\alpha \sim 12^{\mathrm{h}}$, so at sunset, $\alpha \sim 18^{\mathrm{h}}$ is on the meridian. Rigel is thus near the nadir at this time.

1.6. (a) Consider two points on the Earth's surface that are separated by 1 arcsecond as seen from the center of the (assumed to be transparent) Earth. What is the physical distance between the two points?

$$d = \theta R = 1'' \times \left(\frac{\mathrm{rad}}{206265''}\right) \times 6378\,\mathrm{km} \times \left(\frac{10^3\,\mathrm{m}}{\mathrm{km}}\right) \sim 31\,\mathrm{m}$$

(b) Consider two points on the Earth's equator that are separated by one second of time. What is the physical distance between the two points?

$$\theta = 1\,\mathrm{sec} \times \left(\frac{1\mathrm{hr}}{3600\ \mathrm{sec}}\right) \times \frac{360^{\mathrm{o}}}{24^{\mathrm{h}}} \times \frac{\pi\,\mathrm{rad}}{180^{\mathrm{o}}} = 7.27 \times 10^{-5}\,\mathrm{rad}$$

So their physical separation is $d = \theta R = 463.8\,\mathrm{m}$.

1.7. The bright star Mintaka (also known as δ Orionis, the westernmost star of Orion's belt) is extremely close to the celestial equator. Amateur astronomers can determine the field of view of their telescope (that is the angular width of the region that they can see through the telescope) by timing how long it takes Mintaka to drift through the field of view when the telescope is held stationary in hour angle. How long does it take Mintaka to drift through a 1 degree field of view?

The sky appears to rotate westward at the sidereal rate

$$\omega = \frac{360^{\circ}}{24\,\text{sidereal hrs}} = \frac{15^{\circ}}{\text{sidereal hr}}.$$

The time it takes to rotate through an angle θ is

$$t = \frac{\theta}{\omega} = \frac{1^{\circ}}{15^{\circ}\ \mathrm{hr}^{-1}} \times \frac{60^{\mathrm{m}}}{1\ \mathrm{hr}} = 4\,\text{sidereal minutes}$$

In terms of mean solar time,

$$t = 4\,\text{sidereal minutes} \times \frac{23^{\mathrm{h}}56^{\mathrm{m}}\ \text{solar time}}{24^{\mathrm{h}}\ \text{sidereal time}} = 3^{\mathrm{m}}59^{\mathrm{s}}\,\text{solar time}$$

1.8. (a) Imagine that technologically advanced, but highly mischievous, space aliens have reduced the tilt of the Earth's axis from 23°.5 to 0°, while leaving the Earth's orbit unchanged. Sketch the analemma in this case.

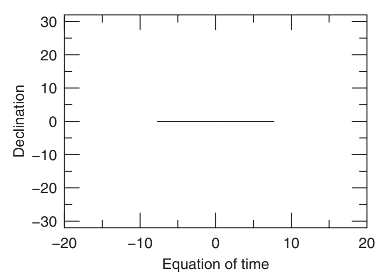

Figure 1.4: The part of the Earth's analemma that is attributable only to the eccentricity of the Earth's orbit. The part due to obliquity has been removed.

(b) Now imagine the aliens have restored the axial tilt to its previous value of 23°.5, but that they have changed the Earth's orbit so that it is a perfect circle, with the Earth's orbital speed being perfectly constant over the course of a year. Sketch the analemma in this case.

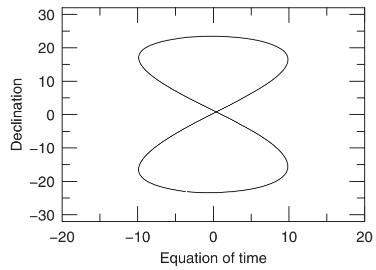

Figure 1.5: The part of the Earth's analemma that is attributable only to the obliquity of the ecliptic. The part due to eccentricity of the Earth's orbit has been removed.

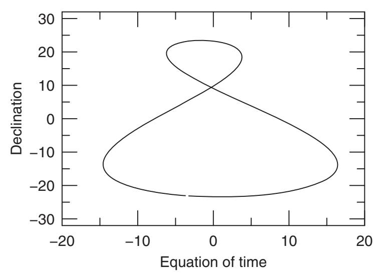

Figure 1.6: The Earth's complete analemma, shown for reference.

(c) The martian analemma is shown in Figure 1.15. What is the tilt of the rotation axis of Mars?

Inspection of the amplitude of the analemma shows that the inclination of Mars must be $\sim 24^{\circ}$ relative to its orbital plane.

1.9. How many square degrees are on the complete celestial sphere?

There are 180° per π radians, so there are 180^2 square degrees in π^2 steradians. Thus, the surface area of the sky in steradians is

$$A = \left(\frac{180^{\circ}}{\pi \text{ rad}}\right)^2 \times 4\pi \, \text{steradians} = 41,253 \text{ square degrees}$$