

UNIVERSITY COLLEGE LONDON

University Of London Observatory PHAS1510 – Certificate in Astronomy, 1213.01

PHAS1510-08 Radio Astronomy: Pulsars

Name: _____

1 Objectives

The objectives of this experiment are to become familiar with acquisition and analysis of radio data for pulsars.

An experienced student should aim to complete this script in 2 (and not more than 3) sessions.

2 Items required

You will need:

- access to a PC running MS-Windows and the CLEA/ULO program ‘Radio Astronomy of Pulsars’, and a scientific pocket calculator. (Before running the CLEA/ULO program you should ensure that the MS-Windows default printer on the desktop of the ULO computer you are using is set to the ‘ULO-NWcolourprinter’. Ask a demonstrator to make the change for you if you are unsure how to do this.)

(This practical is also available on the Certificate’s Web site.)

3 Introduction

[You may wish to read this section ‘off-line’; this background material may be of interest, but is not essential to complete the practical.]

In 1967 a group of radio astronomers at Cambridge, led by Professor Anthony Hewish, were studying the phenomenon of scintillation (‘twinkling’) of astronomical radio sources, arising from density fluctuations in the solar wind. In the course of this work, radio signals were recorded which occurred with astonishing regularity, every 1.3373 seconds. The pulses were so regular that the group first tried to find some terrestrial, man-made source of radiation, such as radar or home appliances, to account for the signals. However, it soon became clear that the source was fixed in a celestial, not terrestrial, frame of reference. The team even entertained the idea, briefly, that they were coming from ‘Little Green Men’. When more pulsing radio sources, or ‘pulsars’, were discovered in different parts of the sky, it became clear that they were a natural phenomenon. The original source was designated CP 1919 (Cambridge Pulsar 1919, at Right Ascension 19h 19m).

The member of the research team responsible for noticing these peculiar regular pulses was Jocelyn Bell, then a postgraduate student of Professor Hewish. Later she worked at the Mullard Space Science Laboratory (MSSL), at that time a part of the Department of Physics and Astronomy at UCL.

Many radio pulsars have since been discovered, and a few have been identified optically or in X-rays. The most famous is 0531+21,* the pulsar in the centre of the Crab Nebula, which has a period of 0.0331 seconds – one of the shortest periods found to date.

The very short periods and the regularity of the pulses have led to the interpretation that the signals are being generated by rapidly rotating, highly magnetic, neutron stars (formed in supernova explosions). A neutron star consists of ‘degenerate’ matter; that is, the protons, neutrons, and electrons are packed together closer than allowed by the classical laws of physics. A neutron star typically has roughly the same mass as our Sun, collapsed into a sphere with a diameter of ~ 15 km.

Neutron stars rotate rapidly because they form from the collapse of normal stars, and those normal stars are invariably rotating. When the star collapses, then, like a skater drawing her arms closer to her body, it spins faster (obeying the principle of *conservation of angular momentum*). Since a neutron star is about 100,000 times smaller than a normal star, it should (and, initially, does) spin roughly 100,000 times faster than a normal star.

As a star collapses to form a neutron star, any magnetic field is also ‘squeezed’ into a smaller volume. As a result, a neutron star has an intense magnetic field associated with it. As the star rotates, this huge magnetic field blows plasma (ionized gas) outwards, giving rise to a beam or cone of electromagnetic emissions at all wavelengths, from radio to X-ray. If the Earth is in the path swept out by this beamed radiation from the pulsar, then an observer can detect the pulses in its spectrum. (This beaming effect is often illustrated by comparison to the operation of a lighthouse.)

4 Experiment

The PC should already be switched on. If the program is not already running, find its icon and double-click the left mouse button to start the program. (In this script an unspecified ‘click’ means you should use the left mouse button; some of the features of the software require the use of the right mouse button and this will always be specified.)

4.1 Operating the ‘Radio Telescope’

After opening the program, begin the experiment by clicking on **File|Login**[†] in the menu bar (at the top of the experiment window).

Enter your name, then confirm by clicking the **Yes** button.

To activate the (virtual) radio-telescope window, click on **File|Run|Radio Telescope** in the menu bar at the top of the experiment screen.

The main window which should appear shows the control panel for the University of London Observatory (ULO) radio telescope (which, unfortunately, only exists in the program!). A viewscreen shows the telescope itself: a large steerable dish, which acts as the antenna to collect radio waves and send them to the receiver. To switch the viewscreen from an impression of the telescope to a computerized view of the sky, click on the **View** button (at the bottom right of the experiment screen).

All ground-based telescopes, whether working at optical or radio wavelengths, have tracking motors designed to keep it pointing at fixed celestial coördinates as the Earth rotates. Initially, the motor of our ‘virtual radio telescope’ is off, and even if the telescope

*Pulsars – like many other objects – are assigned catalogue numbers according to their celestial coördinates. The Crab’s right ascension and declination are $\alpha = 05\text{h } 31\text{m}$, $\delta = +21^\circ$.

[†]This means click on the ‘**File**’ menu, then select ‘**Login**’ from the options offered. In this script, instructions in **this font** always indicate options on the computer screen.

is not moving, the right ascension coördinate shown under the viewscreen is changing (because the rotating Earth is causing the telescope to sweep the heavens). Just below the time displays on the left-hand side of the screen is a button labelled **Tracking**. Click on this button should turn the tracking on; the telescope will then maintain constant celestial coördinates (i.e., the Right Ascension coördinate stops changing) as the Earth rotates. Check that this actually happens.

4.2 Observation of a Pulsar with the Single-Channel Radio Receiver

It's now time to 'observe' a pulsar. From the menu bar, click on **Hot List|View/Select from List...** From the list of objects presented, select pulsar 0628–28. After asking for verification, the telescope will slew towards the pulsar (watch as the displayed coördinates change, or have the **View** set to 'Sky Map').

Once the dish is pointed in the right direction, the radio receiver can be turned on by clicking on the **Receiver** button in the upper right section of the telescope control window. This is your main tool for recording the pulsar signal; a new, rectangular *control window* will open, showing a graphic display of signal strength as a function of time.

Click on the **Mode** button to start observations of the pulsar with the receiver.[‡] The graphical trace shows the signal received as a function of time; it looks like a random jiggle (which is the background static) with an occasional brief but regular rise in signal strength (the pulsar signal).[§]

The frequency (in MHz) of the signal being recorded can be changed by clicking on the relevant up/down arrows in the control window. Experiment with the **Vert. Gain** (vertical gain) up/down arrows in the control window in order to change the amplitude of the displayed signal. The best setting is where the pulses are high, but do not peak above the top of the graphic display. (This setting will vary from pulsar to pulsar, and with frequency.)

The length of time shown in the graphic display is adjusted by using the **Horz Secs** button, but can only be changed when the receiver **Mode** is off (the button is 'greyed out' otherwise). Do this by clicking the **Mode** button again. When the 'horizontal seconds' is set to 4, the graphical trace takes 4 seconds to sweep across the screen. The smaller the value of the horizontal scale, the weaker the signal appears because the receiver is spending less time collecting radio waves before it displays them on the screen. (Astronomers would say the 'integration time' is shorter.)

1. Using pulsar 0628–28 as an example, take a few moments to become familiar with how the above controls affect the display of the received signal. Exam the signal at frequencies of 600, 900, and 1200 MHz. State in the space below how the following vary with frequency:
 - (i) The strength of the pulse signal
 - (ii) The strength of the noise (i.e., the interpulse 'signal')

[‡]The **Mode** button 'toggles' the graphic display on/off; that is, if the display is active, clicking **Mode** renders inactive, and vice versa.

[§]If you are running the program at home, on a PC with a sound card and speakers, there'll be an accompanying audio signal.

4.3 Measuring the Period of a Pulsar

Due to the fact that each pulse detected on the Earth corresponds to one rotation of the source pulsar, it is possible to measure the rotation period of the pulsar simply by finding the time between pulses. With the telescope still pointing at pulsar 0628–28, set the frequency to 600 MHz, the ‘vertical gain’ to 4, and the ‘horizontal seconds’ scale to 4. (The ‘horizontal seconds’ scale can only be adjusted when the ‘mode’ is set to off.)

Start the receiver, let it run for a few seconds to see the pulses and then turn it off again. When the trace stops moving, the time between pulses (i.e., the neutron-star rotation period) can be measured.

Holding down the left mouse button in the graphical display window produces a blue vertical line at the location of the cursor. Centre this line in the middle of one of the pulses near the left side of the screen. Note the blue numbers on the screen, which give the time in seconds at which the pulse was recorded. By holding down the right mouse button, a white line appears which has a similar use to the blue line. Position this line in the middle of the immediately following pulse (which is to the right of the first pulse measured). The difference between the times shown is the period of the pulsar.

2. What is the period of pulsar 0628–28 at 600MHz? Estimate how accurately you can make this measurement. (Note that you may be able to reproduce the measurement virtually exactly; the question is, by how much can you adjust your timings without the settings being clearly wrong.) Repeat the measurement at a frequency of 1200MHz. Give your result, and comment on it.

4.4 Further analysis: the Data Analysis window

In principle, a more precise way of measuring the period is to measure the time elapsed between several pulses, and then to divide by the number of periods that have elapsed. To do this for pulsar 0628–28, first set the **horizontal seconds** control to 16 so that many pulses can be seen on one scan.

Next click the **Record** button, to set it **ON**, then set **Mode** to **Run** to collect one screen’s worth of data (you can click the **Mode** button as soon as data start accumulating; the trace won’t stop until a full screen’s worth of data are collected).

After recording, you’ll be asked to verify the name of the object (click **OK**, then a new ‘Data Properties’ window will pop up. Click **OK**).

Yet another window will appear, asking if you want to save the data. Click **no** (you’re going to work on the numbers at once). This will result in a final window opening, which, according to its title, will allow you to ‘Analyse Current Data’.

This data analysis window should show the entirety of your recorded data. (If it doesn’t, use the **Horz. Zoom** [horizontal zoom] buttons to make appropriate adjustments.)

Use the *left* mouse button to identify a reference pulse at or near the start of the signal record. (At this stage, don't be too fussy about getting the mouse exactly aligned with the pulse.)

Next, use the *right* mouse button to identify the tenth subsequent pulse.

Using the **Horz. Zoom** buttons, zoom in on the display as much as possible. The exaggerated x scale allows more accurate timing measurements to be made, but you'll've lost at least one, and probably both, of your marked pulses. Use the **Horizontal Pan** keys to locate the first reference pulse, and 'tweak' your timing measurement with the *left* mouse button – the result appears in the blue box to the right, labelled 'V'.

Do the same for the second reference pulse, using the *right* mouse button; the result appears in the green box at the bottom of the window.

3. Record the times of the reference pulses, and hence calculate the rotation period of the pulsar 0628–28, giving your answer to an appropriate number of significant figures.

4.5 Measurement of the Pulsar Distances using 'Dispersion'

The great majority of pulsars are too faint to detect at optical wavelengths, so we cannot use their absolute magnitudes to determine their distance. Other methods have to be used. One technique is to use the phenomenon of *dispersion*. All electromagnetic radiation, including radio waves, travels at the same speed in a vacuum ('the' speed of light), but slows down as it moves through a medium. The longer the wavelength (that is, the lower the frequency), the more the radiation is slowed.

Interstellar space is not quite a vacuum; on average, the interstellar medium has a few atoms, and fewer free electrons, in each cubic centimetre. This is enough to slow down electromagnetic waves very slightly. Although the effect is small, the pulses arrive somewhat earlier at higher frequencies than they do at lower frequencies (because the higher-frequency pulses travel faster through the interstellar medium). By measuring the times of arrival of pulses from the same pulsar at different frequencies, the relative delay can be determined. The size of the delay depends on how much material has been traversed, which depends on the distance, and on the density of interstellar material. These ideas are encapsulated in the *dispersion formula*:

$$D = \frac{T_2 - T_1}{124.5[(\frac{1}{f_2})^2 - (\frac{1}{f_1})^2]} \quad (1)$$

where:

D is the distance to the pulsar (in parsecs);

T_1 is the time of arrival (in seconds) of a pulse at radio frequency f_1 (in MHz); and

T_2 is the time of arrival of *the same pulse* at frequency f_2 .

In principle, it doesn't matter which of T_1 and T_2 is the earlier time; but, as a matter of convenience, you should identify T_1 with the numerically *larger* frequency, for which the pulses arrive earliest.

Equation 1 gives the distance from the pulsar to the Earth in terms of the delay in arrival time between radio pulses received at different frequencies. Lower frequencies travel slower, arriving later. Furthermore, the number of charged particles (the electron

density) of the interstellar medium affects the delay, in the sense that the delay increases with increasing density. The numerical constant in eqn. 1 results from the assumption that there is a uniform interstellar electron density of $0.03 \text{ electrons cm}^{-3}$ (a number derived from observations of pulsars at distances determined by using other methods).

As an example of the pulse delay between differing frequencies, go back to pulsar 0628–28. Open the radio receiver window, set the ‘vertical gain’ to 2 and the ‘horizontal seconds’ to 4, and tune the receiver to 400 MHz. Then turn on the receiver, just to make sure you are getting strong pulses.

Stop the receiver and click the **Add Channel** button. The **Add Channel** button adds a second receiver display, below the first, and aligned with it in time. Set the ‘vertical gain’, ‘horizontal seconds’, and frequency to the same values as the first receiver, then set the **Freq Incr** button on the lower receiver to 10 MHz (thereby setting the frequency increment on the second receiver to 10 MHz). Turn on the receivers and tune the second receiver’s frequency to 420 MHz. It may be noticed that the pulses on the second receiver arrive earlier than those for the receiver tuned to 400 MHz.

If the second receiver’s frequency is continually increased, this behaviour will become more apparent. Tune the second receiver slowly, in 10 MHz increments, up to 600 MHz, pausing now and then to watch the scans. Turn off the receivers (‘Mode’). Now open up a third receiver, again using the **Add Channel** button, and tune this receiver’s frequency to 800 MHz, setting the ‘vertical gain’ and ‘horizontal seconds’ to 4.

It should now be clearly seen that the higher the frequency, the earlier the pulse is received.

4.6 Using the Dispersion Formula

Before the dispersion formula can be applied to observations of a pulsar, data for that pulsar must be recorded. The pulsar used for this part of the exercise will be 2154+40. Using the telescope controls, select this pulsar from the ‘Hot List’ (**Hot List|View/Select from List**), and slew the telescope to it.

4. Using the same method as in question 3, determine the pulse period for 2154+40.

5. Generally, the rotation of a pulsar slows down as it ages. From the measured periods of pulsars 0628–28 and 2154+40, infer which is the younger.

Turn on the receivers and observe the pulses. Set up the three channels for 400, 600, and 800 MHz, ensuring that they have suitable vertical gain and horizontal seconds settings in order to observe the time-delay effect for the pulses. (Note that at 400MHz the pulse arrives almost a full period after the 800MHz pulse.)

When each channel's settings are satisfactory, click the **Record** button; this will enable the data recorder. Next, turn the receivers on. Let the receiver scan for five or six screens worth of data and then switch off the receivers. The computer should report that 1600 data points have been saved. It will then show the name of the object for verification. Click **OK**. A 'data properties' box should then appear, showing information about the object recorded. Click **OK**. The data can then be saved in an appropriate file (chosen by the computer from your login name). Now that the data have been saved, they can be analysed.

4.7 Data Analysis

Close the receivers (by clicking on the small \times symbol in the upper right corner of the main receiver window). Once back in the main window, click **File|Run|Data Analysis**. If the program has not been turned off, it will show the general information on the data file last created. Otherwise it will prompt you to use the **File|Load** menu to choose a data file.

When the correct file for data analysis has been selected, a measuring window with three labelled traces will appear. This window is similar to the three receivers previously used, but displays the stored data just loaded. Click on the **Horizontal Pan** arrows to move the traces left and right. Click on the **Horz Zoom** buttons to change the scale of the traces.

To measure the times of arrival of a pulse at the three different frequencies recorded, first zoom in until only two pulses can be seen across the screen. (This high magnification will allow the pulse arrival times to be measured more readily.) Pan the screen so that there is a pulse at the lowest frequency chosen in the right half of the top screen. The same pulse should be seen arriving to the left (at an earlier time) at the next lowest frequency, and still earlier at the highest frequency.

Hold down the left mouse button while moving the mouse in a measuring window to move a vertical line back and forth across the screen. Set one line in the middle of the pulse being observed for the lowest frequency chosen. The arrival time can be read in the blue window to the right of the measuring window. Set measuring lines similarly for the other frequencies used, noting the arrival times. Enter your results in the following Table.

- Using the dispersion formula for radio waves (Equation 1) and the difference in arrival times at any two different frequencies, calculate the distance to the pulsar, entering your results into the table below. There are three different pairs of frequencies, so you can make three different estimates of the distance.

Pulsar 2154+40

f_1 (MHz)	f_2 (MHz)	T_1 (s)	T_2 (s)	$T_2 - T_1$ (s)	$(\frac{1}{f_2})^2 - (\frac{1}{f_1})^2$	D (pc)
600	400					
800	400					
800	600					

- Estimate how accurately you can determine T_1 , T_2 , and T_3 , and thereby estimate, roughly, the uncertainty in the pulsar distance determination arising solely from measurement errors. (The assumption of a known, uniform interstellar electron density introduces an additional error, at a level of perhaps tens of per cent, but don't worry about that.)

Calculate the average distance to pulsar 2154+40 from your three measurements; be careful to quote your result to an appropriate level of precision.

4.8 The Crab Pulsar

8. Slew to the Crab Pulsar, 0531+21. Determine the pulse period using the same procedures as in Q. 3. (Use a frequency of 600 MHz.)

Pulse Period:

9. Estimate the Crab pulsar's distance, using exactly the same technique of dispersion measure as previously.

Pulsar 0531+21 (Crab Pulsar)

f_1	f_2	T_1	T_2	$T_2 - T_1$	$(\frac{1}{f_2})^2 - (\frac{1}{f_1})^2$	D (pc)
605	600					
610	600					
610	605					
Average Distance (pc)						

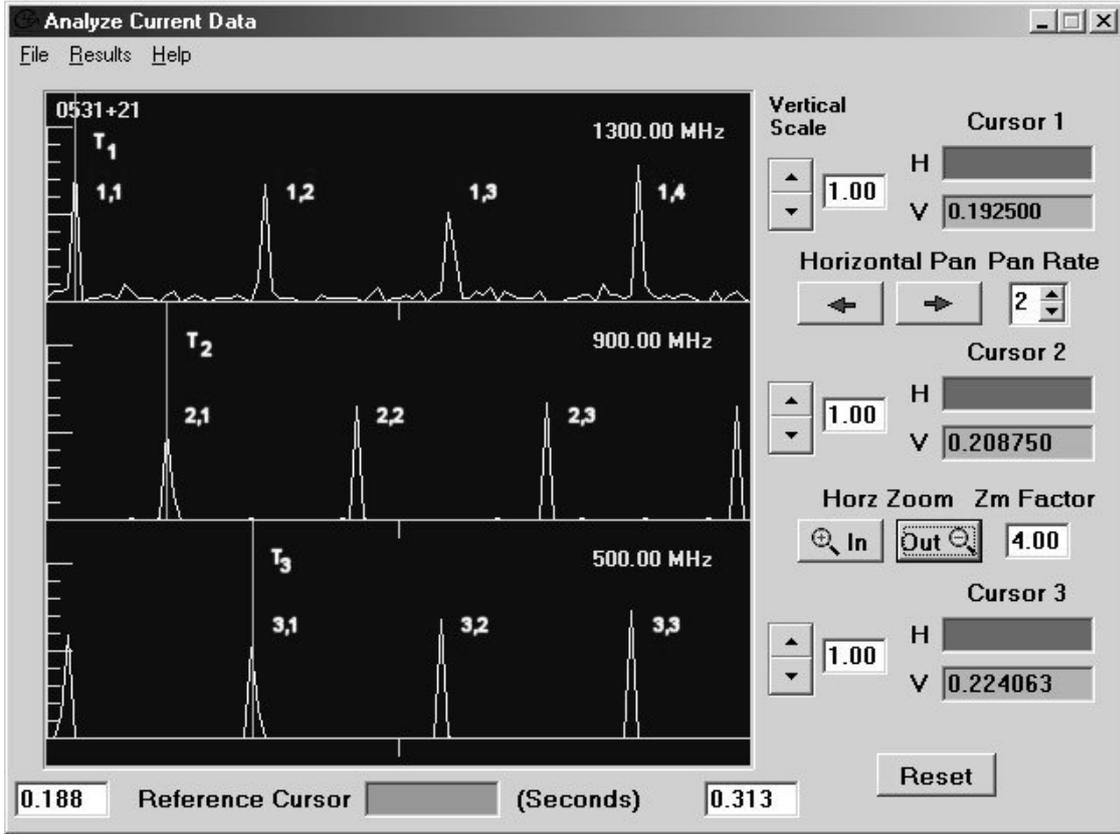


Figure 1: Interpreting the pulse delay for the Crab pulsar (see text).

We can reduce the fractional uncertainty on the pulse delay by using widely separated frequencies (i.e., by increasing the pulse delay). However, because the pulse period of the Crab is so short, even a small change in frequency can delay the signal by almost a full pulse period, as your results should show. If measurements are obtained at widely different frequencies, the pulse delay can be many times larger than the pulse period. In this case, it's necessary to have some idea of the distance in advance, in order to determine the number of 'missed' pulses.

Consider Figure 1. We might be tempted to identify signals (1,1), (2,1), and (3,1) (at times T_1, T_2, T_3 respectively) as originating in the same pulse. But it *might* be that pulse (1,1) actually corresponds to pulse (2,2), exactly one pulse period later; or to pulse (2,3), or to pulse (2,4)..., where each successive delay is exactly one pulse period.

The *true* delay between pulse arrivals at frequencies f_1 and f_2 might therefore be $(T_2 - T_1)$; or $(T_2 - T_1) + P$; or $(T_2 - T_1) + 2P \dots$ (where P is the pulse period). Generalising, we can say the the true delay must be

$$(T_2 - T_1) + iP$$

where i is an (as yet unknown) integer: $i = 0$, or 1, or 2... Similarly, the delay between pulse arrivals at frequencies f_2 and f_3 is

$$(T_3 - T_2) + jP$$

where j is another integer. And finally, the delay between pulse arrivals at f_1 and f_3 must be

$$[(T_3 - T_2) + jP] + [(T_2 - T_1) + iP] \equiv (T_3 - T_1) + iP + jP$$

The corresponding distances are, from eq. 1,

$$D_{21} = \frac{(T_2 - T_1) + iP}{124.5(f_2^{-2} - f_1^{-2})} \quad (2)$$

$$D_{32} = \frac{(T_3 - T_2) + jP}{124.5(f_3^{-2} - f_2^{-2})} \quad (3)$$

$$D_{31} = \frac{(T_3 - T_1) + (i + j)P}{124.5(f_3^{-2} - f_1^{-2})} \quad (4)$$

(where $f_1^{-2} \equiv 1/f_1^2$).

We expect $D_{31} = D_{21} = D_{32}$, within the limits of uncertainty (just because the pulsar distance is frequency independent). By *requiring* that $D_{32} = D_{21}$, we can combine equations 3 and 2 to determine a consistent value of j for any given value of i :

$$\frac{(T_2 - T_1) + iP}{124.5(f_2^{-2} - f_1^{-2})} = \frac{(T_3 - T_2) + jP}{124.5(f_3^{-2} - f_2^{-2})}$$

whence

$$(T_3 - T_2) + jP = \frac{(T_2 - T_1) + iP}{124.5(f_2^{-2} - f_1^{-2})} \times 124.5(f_3^{-2} - f_2^{-2})$$

or, after a little re-arranging,

$$j = \frac{(f_3^{-2} - f_2^{-2})}{(f_2^{-2} - f_1^{-2})} \left[\frac{T_2 - T_1}{P} + i \right] - \frac{T_3 - T_2}{P} \quad (5)$$

Now *physically* we expect j to be precisely integer; but *numerically*, equation 5 will always give values for j that are not quite integer (e.g., because of measurement errors), or perhaps not even close to integer (e.g., because a wrong value for i has been chosen). This gives a pointer to the correct value for i ; it should give a result for j that is fairly close to an exact integer.

- Record pulse measurements for the Crab pulsar at frequencies of 1200, 800, and 400 MHz, and determine values for T_1, T_2 , and T_3 . (Note that these three timings should be monotonically increasing, and $T_3 - T_2$ and $T_2 - T_1$ should each be less than the period, P .) By assuming values of i from 0 to 5, compute possible values for D_{21} (eqtn. 2), and corresponding values for j (eqtn. 5). Enter your results in the Table overleaf.

Based on your previous results (Q. 9), and on how close your computed value for j is to integer, identify what you think is the most probable distance to the Crab pulsar. Using the corresponding (integer) value of j , compute D_{32} and D_{31} , using eqtns 3 and 4.

(*WARNING*: don't assume that your answer should be the same as values you may find in textbooks – there are several ways to determine the distance to the Crab, none of which is particularly accurate!)

5 References and Background Reading

- Zeilik, M. & Gregory, S. *Introductory Astronomy and Astrophysics*, (4th edition). The 3rd edition, by Zeilik, Gregory & Smith, is very similar.
- Freedman, R.A. & Kaufmann, W.J., *Universe*, 7th edition; Chapter 23, especially §§23–2 to 23–4 inclusive.

Pulsar 0531+21 (Crab Pulsar)

f_1 : 1200MHz	T_1 :		
f_2 : 800MHz	T_2 :		
f_3 : 400MHz	T_3 :		
$T_2 - T_1$ (s):	$f_2^{-2} - f_1^{-2}$:		
$T_3 - T_2$ (s):	$f_3^{-2} - f_2^{-2}$:		
$T_3 - T_1$ (s):	$f_3^{-2} - f_1^{-2}$:		
i	$T_2 - T_1 + iP$ (s)	D_{21} (pc)	Inferred j
0			
1			
2			
3			
4			
5			
6			
Adopted distance, D_{21} (pc), and j (integer)			
Computed D_{32} (pc) for adopted j (show working overleaf)			
Computed D_{31} (pc) for adopted i, j (show working overleaf)			
Average of D_{21} , D_{32} & D_{31}			