SOCIETY OF PHYSICS STUDENTS
An organization of the American Institute of Physics

SPS Chapter Research Award Proposal

Project Proposal Title	Construction of a radio telescope for the 21 cm hydrogen line
Name of School	Universidad Autónoma de Ciudad Juárez
SPS Chapter Number	3291
Total Amount Requested	$1,853.41

Abstract

The SPS chapter at our university plans to build a relatively small radio telescope capable enough to make detections of the hydrogen emissions occurring in the galactic center. We intend to take the recreational-only astronomical observations that already have place in our university to a student-research-level by building and operating a fully functional radio telescope.

Proposal Statement

Overview of Proposed Project

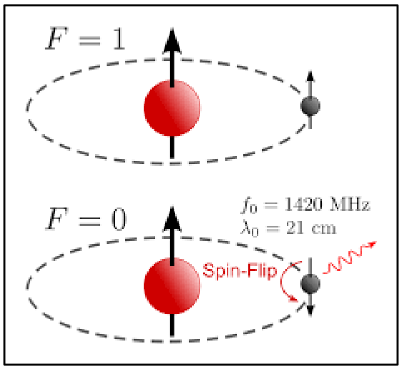

Figure 1 Hydrogen atom spin flip [9].

With the equipment we are planning to acquire, we will be able to study the hydrogen spectral lines present in our galaxy, and at the same time with the construction, operation, and data acquisition, students involved in the SPS chapter will be able to conduct other research projects. The radiation that we are focusing on is the radiation emitted by hydrogen when it passes from the state where the proton and electron spins are parallel to the state where the spins are antiparallel; this transition between these two states emits radiation in a wavelength of about 21 cm which corresponds to a frequency of about 1420 MHz, as will be explained below.

For undergraduate students, radio astronomy can be a complicated field to get into because current research is made using gigantic antennas, or arrays, and not all students have the opportunity to work with a radio telescope before their graduate studies. Our proposal would make that gap smaller by giving undergraduate students a hands-on experience on the setup and operation of a radio telescope and on the analysis of collected data. The activities planned for the radio telescope will be paired with those offered by the astronomy club in our university, thus benefiting the Ciudad Juarez community by inviting more people to our outreach activities, especially high-school students interested in the engineering physics program at our university.

Figure 2 The Atacama Large Millimeter Array in Chile is one of the biggest radio telescopes arrays [10].

The radio telescope consists mainly of a parabolic antenna, whose focal radius can be calculated so the detector placement is optimal. The signal captured by the antenna and the detector is sent to the spectrometer, then the spectrometer in principle could work in two modes; the *continuum mode* shows only a specific frequency (in this case, the 1420Mhz line of the transition between hydrogen states present in the galactic clouds). In the *spectral mode*, it measures the spectral distribution centered on the 1420 MHz, but scanning a specified interval, so the spectrum width could be of about 1200 MHZ. While doing this, it is important to consider the Doppler effect due to the relative motion of the source and detector.

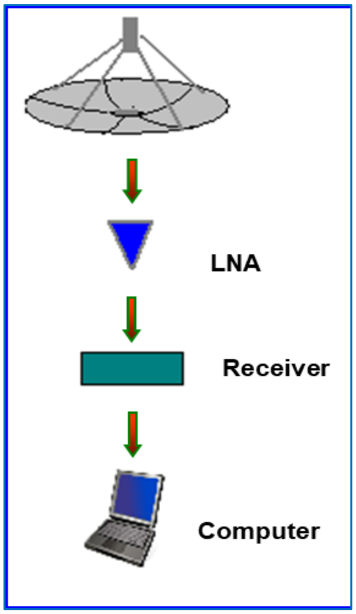

Figure 3 Radio telescope basic components [11].

Given the signal properties, it is important to use a low noise amplifier (LNA) and carry the signal from the detector to the spectrometer to be adequately registered. The signal is carried in coaxial cables, the ones used in telecommunications. To get rid of as much noise as possible it is important to maintain the LNA and cables as cool as possible.

Figure 4 A member of the Astronomy Club giving instructions on how to operate the telescope

The goals we expect to achieve with this research are the following:

- Build and operate the radio telescope.
- Properly test the radio telescope using a calibration source.
- Make detections of the radiation emitted by the transition happening between the hydrogen states.
- Store and analyze data from the detections.
- Develop new projects supported by the radio telescope research, construction and operation.
- Use the radio telescope for science outreach the Ciudad Juarez-El Paso binational community.

We hope to encourage more students that participate in the outreach activities to take part in research projects at earlier stages of their education and also to contribute to the development of a greater interest in physics and astronomy among the children that often join our astronomical observations. With a project like the one described here, the SPS program in our university would become more diverse by encouraging a greater participation, thus motivating more projects, in multiple areas of physics, to be proposed in the near future. By having the opportunity to work on our radio telescope project we'll acquire valuable research experience important to our professional careers, by giving us a preview of even larger projects in the near future.

Background for Proposed Project

Radio astronomy was born in the early 1930s when a Bell Laboratories employee found a strange noise source that was showing up in receivers operating in the 20 MHz region of the radio spectrum, this man was Karl Jansky, an American radio engineer and physicist considered the one of the founding figures of radio astronomy; Jansky discovered that this noise he detected was from extraterrestrial sources, at the time this discovery from Jansky did not have much attention from the scientific community. Nevertheless, there where a few individuals interested enough to continue with Jansky's work.

Grote Reber was one of them, an electronics engineer and avid radio amateur speculated that the signals Jansky discovered were from thermal origin and they would be easier to detect at higher frequencies. Reber built a receiver and antenna for a 3000 MHz operation frequency. Although he did not prove his hypothesis, by the late 1930's he accomplished the first radio map of the galactic plane and built the first radio telescope by himself, even though the term had not been coined yet.

The development of radio telescopes has been done thanks to the search of noise from the universe, this noise bears witness to the physical characteristics of the universe [12].

The 21 cm line of hydrogen was detected in 1951 by three different research groups in the Netherlands led by Oort and Muller, a team in Harvard in the US led by Ewen and Purcell and a team in Australia led by Christiansen and Hindman, all detecting the 21 cm line within a few weeks of each other, they all reported their findings in the same edition of Nature [1]. As had been foreseen, the prediction of the 21 cm line proved to be of great fundamental importance, a basic step in establishing a valuable method of studying the structure of the galaxy.

In the quantum theory of the hydrogen atom, as explained in [7], the proton's and electron's magnetic moments are

$$\vec{\mu}_p = \frac{g_p\, e}{2\, m_p}\, \vec{s}_p \qquad ; \qquad \vec{\mu}_e = -\frac{e}{m_e}\, \vec{s}_e$$

Were e is the electric charge, m_p and m_e are their respective masses, $\vec{s}_p$and $\vec{s}_e$ are the proton spin and electron spin, and g_p is a g-factor, which is measured to be 5.59 for the proton and 2 for the electron.

The magnetic field of a dipole $\vec{\mu}$ is given by

$$\vec{B} = \frac{\mu_0}{4\pi r^3}[3(\vec{\mu}\cdot\hat{r})\hat{r} - \vec{\mu}] + \frac{2\mu_0}{3}\vec{\mu}\,\delta^3(\vec{r})$$

Where $\delta^3(\vec{r})$ is the Dirac delta function in three dimensions; this means that the hyperfine splitting in hydrogen is produced the magnetic field due to the proton's magnetic dipole. The Hamiltonian of the electron in this perturbation is

$$H^1{}_{hf} = \frac{\mu_0 g_p e^2}{8\,\pi\, m_p m_e} \frac{[3(\vec{s}_p\cdot\hat{r})(\vec{s}_e\cdot\hat{r}) - \vec{s}_p\cdot\vec{s}_e]}{r^3} + \frac{\mu_0 g_p e^2}{3 m_p m_e}\vec{s}_p\cdot\vec{s}_e \delta^3(\vec{r})$$

In perturbation theory, the first-order energy correction is the expectation value of the perturbing Hamiltonian:

$$E^1{}_{hf} = \frac{\mu_0 g_p e^2}{8\pi m_p m_e}\langle \frac{3(\vec{s}_p\cdot\hat{r})(\vec{s}_e\cdot\hat{r}) - \vec{s}_p\cdot\vec{s}_e}{r^3}\rangle + \frac{\mu_0 g_p e^2}{3 m_p m_e}\langle\vec{s}_p\cdot\vec{s}_e\rangle|\Psi(0)|^2$$

It happens that the first term vanishes in the ground state. Also, we find that

$$|\Psi_{100}(0)|^2 = \frac{1}{(\pi a)^3}$$

The first-order correction to the energy becomes

$$E^1{}_{hf} = \frac{\mu_0 g_p e^2}{3\,\pi\, m_p\, m_e\, a^3}\langle\vec{s}_p\cdot\vec{s}_e\rangle$$

Since the total spin is

$$\vec{S} = \vec{s}_p + \vec{s}_e$$

And squaring

$$S^2 = s_p{}^2 + s_e{}^2 + 2\,\vec{s}_p\cdot\vec{s}_e$$

Then

$$\vec{s}_p\cdot\vec{s}_e = \frac{1}{2}\left(S^2 - s_p{}^2 - s_e{}^2\right)$$

Since the proton and the electron are spin-1/2 particles

$$s_e{}^2 = s_p{}^2 = \frac{3}{4}\hbar^2$$

In the “parallel” spins state (the triplet state) the total spin 1 and $S^2 = 2\hbar^2$. In the single state the total spin is 0, and $S^2 = 0$.

The first-order correction to the energy is then

$$E_{hF}{}^1 = \frac{4\, g_p\, \hbar^4}{3\, m_p\, m_e{}^2\, c^2\, a^4}\begin{cases} +\frac{1}{4}, & \textit{triplet state} \\ -\frac{3}{4}, & \textit{singlet state}\end{cases}$$

Where a is the Bohr radius.

The transition between these states has an energy gap given by

$$\Delta E = \frac{4\, g_p\, \hbar^4}{3\, m_p\, m_e{}^2\, c^2\, a^4} = 5.88\times 10^{-6}\ eV$$

This energy corresponds to the energy of the emitted photon in a transition from the parallel spin state (triplet state) to the antiparallel spin state (singlet state). The frequency of the emitted photon is

$$\nu = \frac{\Delta E}{\hbar} = 1420\ MHz$$

Which corresponds to a wavelength $\lambda = \frac{c}{\nu} = 21\ cm$, this is the 21-cm hydrogen line produced in the galactic center which can be detected with our proposed radio telescope.

Expected Results

The results we are expecting to get from this research can be separated into 3 categories: installation results, data acquisition results and detection. During the first stage of this research proposal we need to install the antenna to then set-up the detectors on the antenna, then connect all of the components of the radio telescope and install the software that we will use to see the signal. After we complete the installation, we should be able to measure the signals and, if all the installation is correct, the signal should be easily identified in the computer.

Once we are sure our radio telescope is correctly detecting signals, we have to ensure that our data from the signals is being stored in the computer to be analyzed later, which is going to be done using different programming languages and software. In case that the data takes too much space, we would look for options of bigger storage.

After all the set-up and by pointing our antenna in the direction of the galactic center, the main result of our project would be the detection of the 21 cm spectral line emitted by the hydrogen clouds passing by. Our antenna should be able to intercept this signal and this data would be stored in our server to be analyzed.

Description of Proposed Research - Methods, Design, and Procedures

The radio telescope will be installed on the top of a building inside the university, this building has easy access to the roof and there will be no problems with the transportation of components from the ground floor to the roof. The antenna's base is going to be screwed on to the roof and will be pointing in a fixed direction to receive the expected signal once every day, the signal received will be carried out by a coaxial cable to the control room, located in one of the rooms of our physics laboratory, which will have the computer with the software required to analyze the signal and to store the data. We are going to be doing several test runs using noise sources and different sources like the sun or radio frequency emitters.

For the signal receiver we are using an SDR device, in this case the FUNcube, which is lower in cost than a professional spectrometer, and has a frequency coverage from 50 MHz up to around 2000 MHz. It is important to make some measurements of the frequency stability and the gain and noise for the device, these tests have to be done with help from the software; frequency control software for the FUNcube, and a spectrum viewer called SpectraVue, although there are other options that we are going to explore, like Radio SkyPipe, the operation of these software options is highly detailed in the documentation for each; the basic idea is that we are going to visualize the emission of the galactic center in the spectrum visualizer in an suitable time interval.

To conduct the measurements of the emission from the galactic plane it is necessary to plan the timing and pointing parameters for the experiment. This can be done by using the Radio Eyes software which presents a picture of the radio sky at 1420 MHz along all requested geometric and astronomical axes.

Plan for Carrying Out Proposed Project

Five SPS members will be involved in the research activities: Alan Barraza, Angel Sosa, Dayra Torres, Fernando Terrazas and Sergio Gonzalez are developing the project proposal and, if awarded with this grant, they all will participate in the installation of the radio telescope. Different groups are going to be created to distribute responsibilities of the calibration, software installation, operation, and storage. All the participants have experience in astronomy, most participate in our university's astronomy club, so they are familiar with the coordinates and localization of astronomical objects. Others are familiar with signal processing and spectrometry. The team will be supervised by Dr. Jesus Saenz, who is acquainted with signal detection and analysis.

The workspace is a laboratory building inside the university. The antenna is going to be placed on the roof of the aforementioned building, and in one of the rooms of the physics laboratory we are planning to set the computer and other things we might need in the future, some conditioning for the building is necessary and accessible, so the cables would not be over-exposed to outdoors.

Project Timeline

Activity	January	February	March	April	May	June	July	August	September	October	November	December
Team reviews documentation of software and equipment that wil lbe used	■	■										
Buy components to start assembly			■									
Planning and installation of equipment			■	■								
Preliminar components and software tests				■	■							
Submint interim report					■							
Buy the rest of the components						■						
Finalize radio telescope installation							■	■				
Calibration and first test runs								■	■			
Data acquisition									■	■		
Analyze all data acquired									■	■	■	
Submint final report												■

Budget Justification

The budget we are asking for in this proposal is going to be used for buying the equipment necessary for the radio telescope. The components that are going to be bought are the FUNcube SDR, a specific LNA for detecting the hydrogen line frequency, a cooler module to get a clearer signal. Some complements for the antenna are also needed for the signal to be detected in the most efficient way; a feedhorn and choke designed specifically for the 1420 MHz, and a 1420 MHz noise source for calibration purposes.
Most of the components specifically designed for the 1420 MHz frequency are going to be acquired from Radio Astronomy Supplies, a specialized radio astronomy components online store.

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