

Spectroscopic Determination of White Dwarf Candidates for the Dark Energy Survey

Mees B. Fix

Department of Energy Visiting Faculty Program

Department of Physics & Astronomy

Austin Peay State University

Clarksville, TN 37044

Fermi National Accelerator Lab

Batavia, IL 60510 USA

ABSTRACT

The Dark Energy Survey (DES) is a current project in Fermilab's Cosmic Frontier which is a 5000-square-degree optical/near infrared imaging survey conducted over five years (2013-2018) for purposes of measuring the properties of dark energy. Synthetic photometry of pure-hydrogen-atmosphere ("DA") white dwarfs is currently the preferred technique for absolute zeropoint calibration of large sky surveys. For absolute calibration of the DES there needs to be a "Golden Sample" of 30-100 DA white dwarfs developed. The starting point is a photometric and spectroscopic observational campaign of ~ 6000 candidate white dwarfs in the DES field. Analyzing imaging and spectroscopic data will allow us to narrow down this sample. Over 50% of the candidates are DA white dwarfs.

1. Introduction

Early in the 20th century Edwin Hubble made the discovery that the universe is expanding [1]. According to the standard model of cosmology, this is due to energy left over from the Big Bang. Until the late 1990s, the science community was in general agreement that this expanding was due to the mutual gravitational attraction of matter in the universe. But in 1998 scientists discovered that the universe was not only expanding but this expansion was accelerating [3], [4]. Our understanding of physics requires that there has to be some source that is responsible for this acceleration but there is no visible or explainable reason. This is what is now call "dark energy."

2. Background

2.1. History of Dark Energy

When modifying his equations for the General Theory of Relativity, Albert Einstein introduced what he called the cosmological constant (Λ). Einstein believed the universe was static, which means that the universe is not moving or changing shape or size but is standing still. This constant was introduced into the equations to balance the attractive force of gravity to the repulsive force of the energy left from the Big Bang. Shortly after these modifications Edwin Hubble discovered that universe was not static but indeed expanding. This led to Einstein abandoning his idea of the cosmological constant which he later said was "the biggest blunder of my career" [5]. For the remainder of the 20th century, most scientists believed the universe was expanding at a decreasing rate until the late 1990s when two independent teams discovered that the expansion of the universe is accelerating. These teams were awarded the Noble Prize in Physics in 2012.

2.2. The Standard Model of Cosmology

After the discovery that the expansion of the universe was indeed accelerating led to what we now call the Standard Model of Cosmology. The model states that most of universe is composed of things we cannot directly observe like dark energy and dark matter. Although we haven't observed these things via electromagnetic radiation, we can see their effects on normal (baryonic) matter by gravitational interaction. Figure 1 shows the ratios of everything that composes the universe as we currently perceive it.

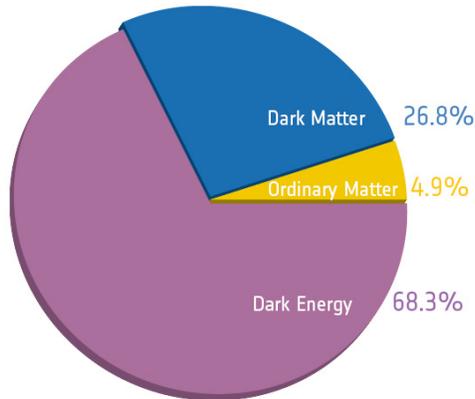


Fig. 1. The Standard Model of Cosmology

3. The Dark Energy Survey

The Dark Energy Survey (DES) involves more than 120 collaborating scientists from 23 different organizations who have bound together to survey a large portion of the sky in the southern hemisphere using state-of-the-art-equipment. The DES will cover a 5000 square degree area of the sky over 525 nights using the Dark Energy Camera (DECam) which is mounted on the 4-meter Blanco Telescope at the Cerro Tololo Inter-American Observatory (CTIO) in the Andes of Chile [6], [7]. The DES will survey objects to a magnitude of 24, and a red-shift of $z \approx 1.5$ using DECam [8]. DECam is a 570 mega-pixel CCD-based research camera built at Fermilab, composed of 74 different CCDs, and has a focal-plane-area of 3.1 square degrees [8]. The DES will observe over 300 million galaxies in five different filters (grizY) to obtain as much information about the galaxies as possible to hopefully explain some of the properties of dark matter.

3.1. Dark Energy Probes

The DES science teams will use four probing methods to constrain the parameters of the dark energy equation-of-state. These four probes are [6]:

- Type Ia Supernovae (SN)
- Baryon Acoustic Oscillations (BAO)

- Galaxy Clusters (GC)
- Weak Gravitational Lensing (WL)

These four techniques are complementary in that information they provide will better explain the cosmic expansion. The first two (SN and BAO) constrain the expansion of the universe as a whole and are referred to as completely geometric. The last two (GC and WL) better explain the expansion and the growth of large-scale structures within the universe.

3.2. Photometric Standard Stars, White Dwarfs, and the DES

Using standards to explain physical phenomenon are important for calibration in any experiment but are more challenging for objects in space. The best method for setting a baseline in astronomy is what is called a photometric standard star. A photometric standard star is a star which has had its magnitude (brightness) measured carefully through different filters. In other words, the apparent magnitude of the star can be repeated experimentally and shows the star is stable. The tool of choice for calibration of large astronomical surveys is synthetic photometry of white dwarfs developed using the observational data. A white dwarf is the degenerate core of main sequence star that is $\approx 8M_{\odot}$ or less that has shed its outer layers during the later periods of evolution. Our current understanding of process leads us to believe that approximately 97 % of stars will become white dwarfs. White dwarfs are also very dense and can be compared to taking all the mass of the sun and shrinking it down to the size of Earth. Just as stars are classified using the Morgan-Keenan system, white dwarfs have their own classification and spectral characteristics. The white dwarf that we are interested in for absolute calibration have pure hydrogen atmosphere and are classified as "DA." This classification of white dwarfs accounts for ~ 75 % of all white dwarfs in the universe and have temperatures ranging from 6000K to 80000K [12]. A way to easily identify DA white dwarfs is through spectroscopic reductions because of the broadened Balmer absorption lines observed in the spectrum. We use these standard stars by comparing the flux of the standard to other objects in the survey and thereby derive brightness for the science targets. For the absolute calibrations of the DES it is important to have a "Golden Sample" of DA white dwarfs, which will be the calibration standards of the project. Development of the "Golden Sample" is accomplished through spectroscopic identification of the candidate white dwarfs and analysis of the spectrum to derive the surface gravity, effective temperature, and atmospheric compositions of each star. My project to support this effort is to obtain basic one-dimensional spectra of these white dwarf candidates which have been wavelength and flux calibrated.

4. Observations

All of the data for this project were collected at the Cerro Tololo Inter-American Observatory (CTIO) using the 1.5-m telescope with a RC spectrograph in the Chilean Andes and Apache Point Observatory (APO) with the 3.5-m ARC telescope with a Dual-Imaging Spectrograph (DIS) in New Mexico.

4.1. CTIO-1.5-m Dataset

This data set contains information from the 1.5-m at CTIO which has observations from the northern winter of 2013. Table 1 contains the dates of observation along with the number of imaged white dwarf candidates.

Date Observed	Number of WD Candidates
01/03/2013	5
01/10/2013	6
01/22/2013	2
02/03/2013	1
02/11/2013	4
02/17/2013	4
02/20/2013	2

Table 1: Table of Observing Dates and Number of Imaged WD Candidates with the CTIO 1.5-m

4.2. APO 3.5-m Dataset

This data set contains information from the 3.5-m at APO which has observations from the early winter and late fall of 2012. Table 2 contains dates of observations along with the number of imaged white dwarf candidates.

5. Methods

Both sets of spectroscopic data were reduced using the packages from the Image Reduction and Analysis Facility (IRAF) software. IRAF is a general purpose software that is used for

Date Observed	Number of WD Candidates
01/17/2012	8

Table 2: Table of Observing Dates and Number of Imaged WD Candidates with the APO 3.5-m

the reduction and analysis of scientific data written and supported by the IRAF programming group at the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. IRAF has many practical purposes that span from analysing Hubble Space Telescope, X-ray, EUV, photometric, and spectroscopic data. Below are lists of the basic processing steps for 1-dimensional and 2-dimensional data using IRAF.

- Processing 2-Dimensional Data
 - Preparing master flats and biases.
 - Bias subtracting and flat dividing science images.
- Processing 1-Dimensional Data
 - Extracting 1-dimensional Apertures.
 - Arc Lamp Wavelength Calibrations
 - Standard Star Flux Calibrations.
 - Combining Step Using doslit
 - Combining Calibrated Images.

5.1. Processing 2D Data

5.1.1. *Preparing Master Flats and Bias Frames*

1. The first step in processing is to remove the bias voltage in the images caused by the offsets from reading out a CCD camera. Without proper bias subtractions the flat field calibrations mentioned later in this section will not work properly. A bias frame is essentially a zero length exposure with the shutter of the camera closed. Each pixel will have a slightly different value, but except for a small amount of readout noise. Each image will have the same read out noise for each pixel which means since it does not vary it can be subtracted from the images. This noise is created by the electronics when the CCD is read and for very sophisticated instrument this noise can be very

low but never zero. The noise can be suppressed by combining multiple bias frames which then can be used to subtract from scientific images. The bias of a single camera is constant over certain periods of time. It is important to note that some cameras have small bias dependencies on temperature. Although they are small it is still worth noting that it can affect the flat fielding process. Each pixel in each camera has a different sensitivity to light. These sensitivities add noise to scientific images unless certain measures are taken to correct them. This is important for achieving scientific quality images and are absolutely essential for accurate photometric measurements. To create a flat frame, the optical system is illuminated by a uniform light source and then an image is taken. The flat field is then normalized by dividing each pixel into the average value of the array. Any pixel that is more sensitive will be given a value less than one where as a pixel that is less sensitive will be given a value slightly larger than one. When this frame is multiplied across a raw image this will then observing was done on remove the variation of the sensitivity. Usually on an observing run multiple flat frames will be taken and then while processing the images from the run rather than using a single flat an average of all the flats taken is used to eliminate more of the variance in sensitivity of the imaging instrument [10], [11].

2. The combining processes are performed in IRAF with the commands **zerocombine** (zero frame and bias frame mean the same thing) and **flatcombine**. After combining flat and bias field images they can be used to by IRAF to subtract the bias offset level away from raw science images using the **ccdproc** command. For more information on this process visit the IRAF site (mentioned in the bibliography).

5.2. Processing 1D Data

There are three major components to obtaining a 1-dimensional spectrum using IRAF. They are extraction, wavelength calibrations, and standard flux calibration. Below are the components and what they do.

5.2.1. Extraction

1. Finding the spectrum: This is done by examining the cut of the stellar spectra along the spatial axis of the detector [9].
2. Define the extraction window and background windows: This is done by specifying the size of the extraction window in terms of numbers of pixels to the left right and center

of the spatial profile, and the number of pixels to the left and right of the center profile. The background regions are defined similarly to the lower left and right regions of the center profile. This can be altered by viewing the cut along the spatial axis [9].

3. Trace the center of the spatial profile as a function of the dispersion axis: Even though we assume that the spatial axis is along the row or column, the spectrum will generally not be exactly perpendicular with the spatial axis. This process will be sure to map the slight deviation of the spatial profile along the dispersion axis [9].
4. Sum the spectrum within the extraction window, subtracting sky: At each point along the dispersion axis the data that was within the extraction aperture is summed and then sky background subtracted [9].

After this process is complete you have extracted a 1-dimensional spectrum from a 2-dimensional image. The next step is to perform a wavelength calibration. This step takes the 1-dimensional spectrum extracted and changes the x-axis from pixels to units of length typically measured in angstroms (\AA)

5.2.2. Wavelength Calibration

1. Extract a 1-dimensional spectrum from the appropriate comparison exposure using the identical aperture and trace used for the object you are planning to calibrate [9].
2. Determine the dispersion solution for this comparison spectrum. This can be done interactively the first time, and the solution used as a starting point to determine the dispersion solution for the other comparison exposures [9].
3. If the second comparison exposure will be used for providing the wavelength calibration for the object spectrum, repeat steps 1 and 2 for the second exposure [9].
4. Using the dispersion solutions, put the object spectrum on a linear wavelength scale by interpolating to a constant delta wavelength per pixel [9].

After completing the wavelength calibrations next is to calibrate for flux using a spectrophotometric standard star. This is the final step to finish calibrations for a stellar spectrum.

5.2.3. Flux Calibration

Using images from a spectrophotometric standard star one can use the information to calibrate the units on the y-axis from counts to absolute or relative flux units. A spectrophotometric standard star is observed each night [9].

5.2.4. Combining Steps Using *doslit*

The IRAF tool known as **doslit** combines all of the fore mentioned steps into one. This application accepts a list of science, arc lamp, and standard star exposures. After extracting the 1-dimensional spectra and identifying the first arc comparison lamp *doslit* takes care of the rest by wavelength and flux calibrating all of the spectra in the science exposure list. This allows for a night’s worth of spectroscopic data which can take days by hand to be processed in a matter of 10-20 minutes [9].

5.2.5. Basic Final Steps For New Spectra

Now that the processing is complete the last step is to combine all of the single images and make an average image for each candidate. This can be done by using the *scombine* (spectrum combine) command in IRAF which will help eliminate noise, cosmic rays, and other blemishes to the final spectra [13].

5.2.6. *DIStools* (For APO Data Only)

All of the reduced APO spectra was done using *DIStools* which is a script shell that calls IRAF commands and allows for data that was taken at APO to be reduced quickly and precisely. To read more about *DIStools* I will provide a link in the bibliography.

6. Results

6.1. CTIO 1.5-m Results

Using the methods described I was able to obtain spectra of the DA white dwarfs described in section 3.2. The results from this set is shown in the table labelled "Table 3."

Date Observed	Number of WD Candidates
01/03/2013	1
01/10/2013	2
01/22/2013	1
02/03/2013	1
02/11/2013	4
02/17/2013	2
02/20/2013	2

Table 3: Table of Observing Dates and the Number of Confirmed DA WD Candidates.

If compared with "Table 1" over half of the observed candidates are DA white dwarfs. For spectroscopic results, refer to "Figure 2" which has all plotted DA white dwarf spectra.

6.2. APO 3.5-m Results

Date Observed	Number of WD Candidates
01/17/2012	6

Table 4: Table of Observing Dates and Number Confirmed DA WD Candidates

If compared with "Table 2," over half of the candidates are DA white dwarfs. For spectroscopic results, refer to Figure 3 which has all plotted DA white dwarf spectra. It is important to note subfigures e and f have missing information in their spectra. In Figure 3 subfigure f has large emission peaks in the center of the absorption lines. This means there is material or possibly a close by companion star that is shedding material onto the white dwarf. The large emission peak in the h-alpha line caused an issue with the flux calibration on the red CCD. So to scale and eliminate the added flux, parts of the spectrum had to be removed. This causes the gap seen in the 5500-6000 Å region. Subfigure e, not having the emission lines, had a similar problem with the red flux calibration. Although I can't explain the issue with the calibration, the candidate is indeed a DA white dwarf.

7. Conclusions

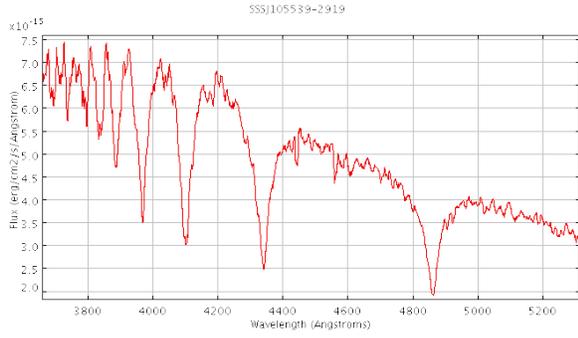
In summary, using the spectroscopic reduction packages in IRAF makes it possible to obtain spectra to classify possible white dwarf candidates for the DES. The total number of candidates narrowed down from both observing runs is 19 with the CTIO dataset having 54 % of the candidates being DA white dwarfs and the APO dataset having 75 % of the candidates being DA white dwarfs. Knowing the classifications of these white dwarf candidates allows for further follow up observations to determine whether these candidates are worthy of being included into the "Golden Sample" and which can be rejected from the sample but now have a stellar classification. The contribution of these spectra is another step forward in the absolute calibrations for the DES.

Acknowledgements

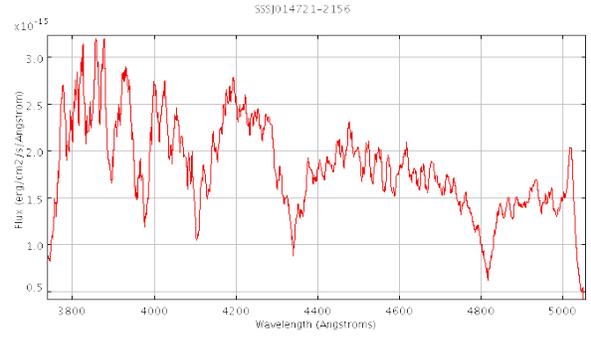
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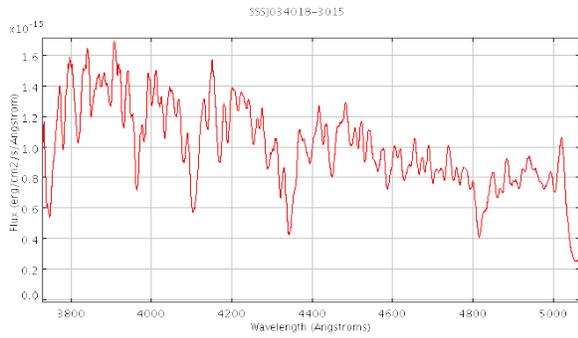
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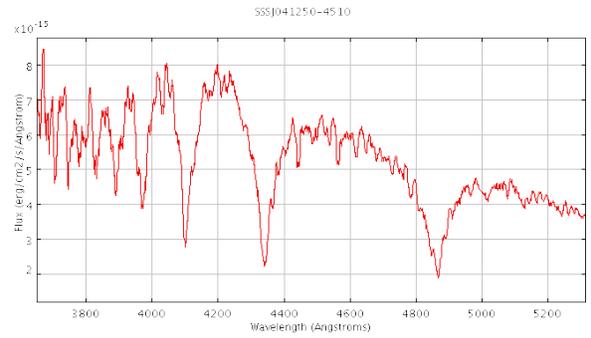
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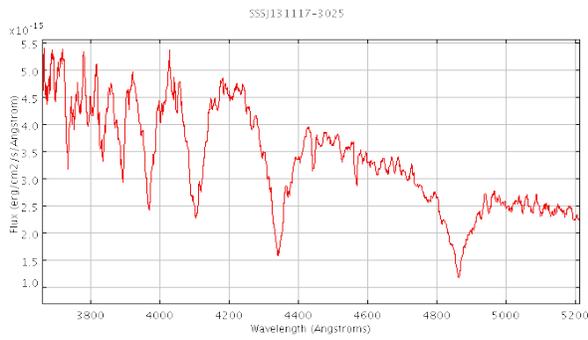
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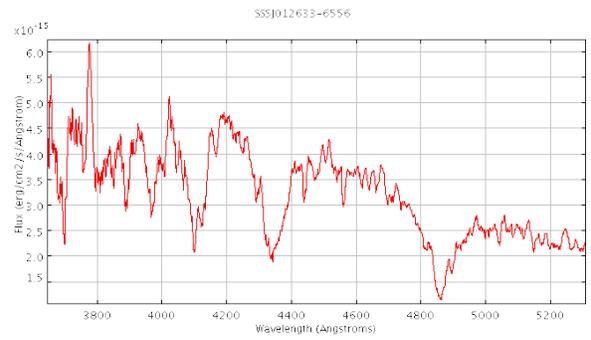
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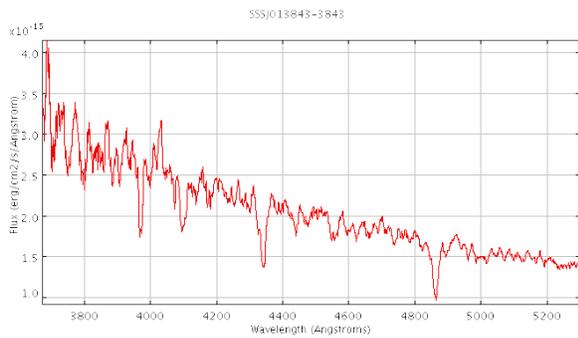
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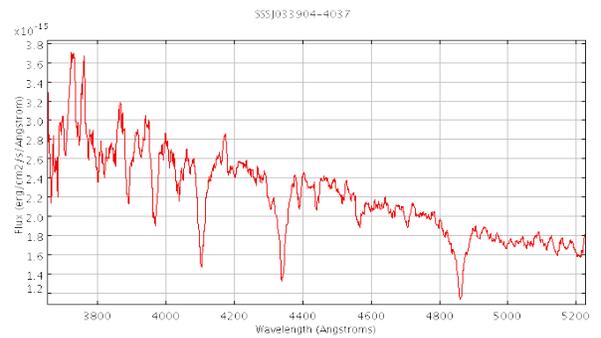
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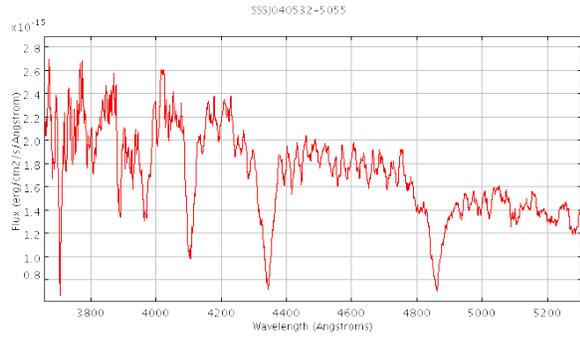
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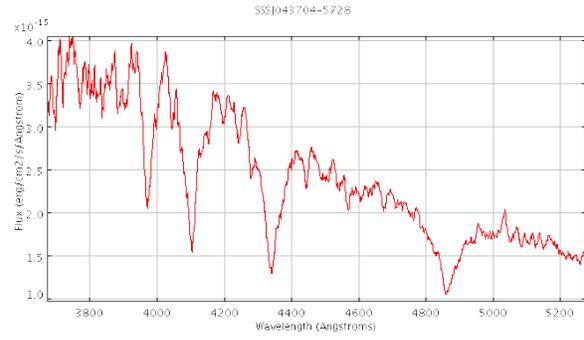
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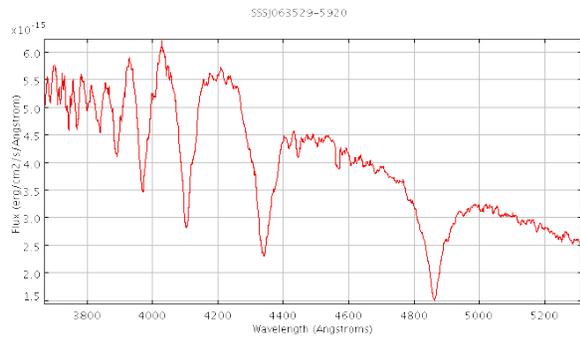
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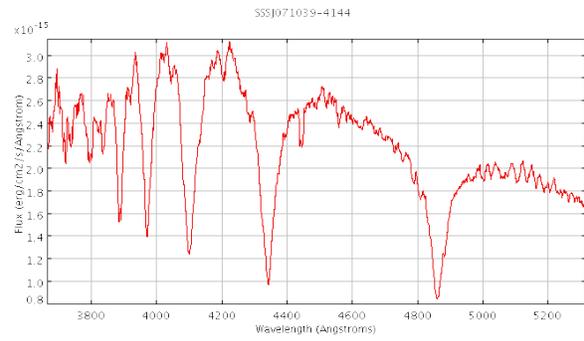
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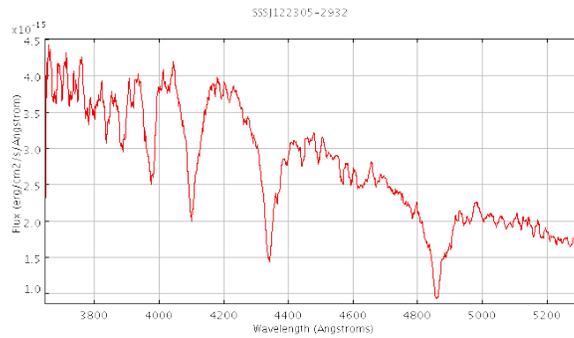
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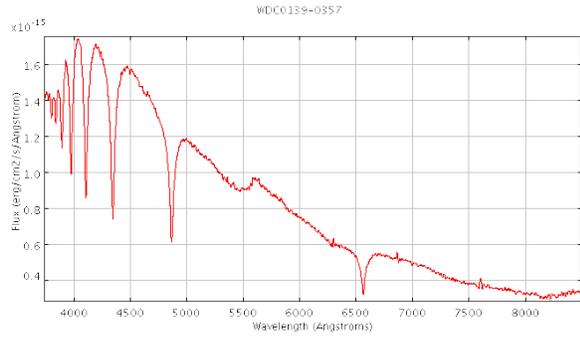


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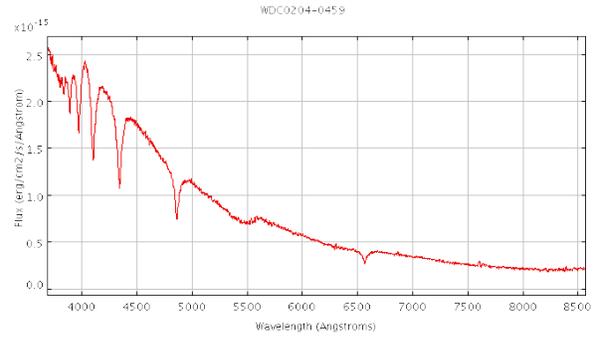


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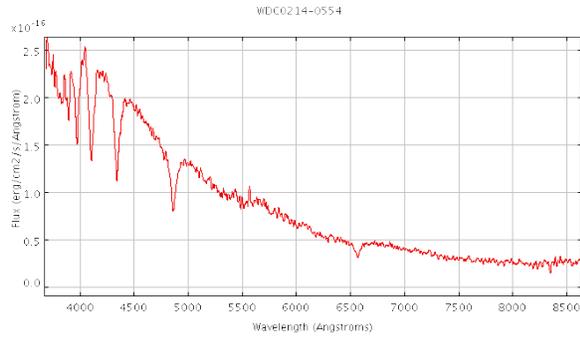
Fig. 2.— Spectra of DA White Dwarfs Found in CTIO Dataset



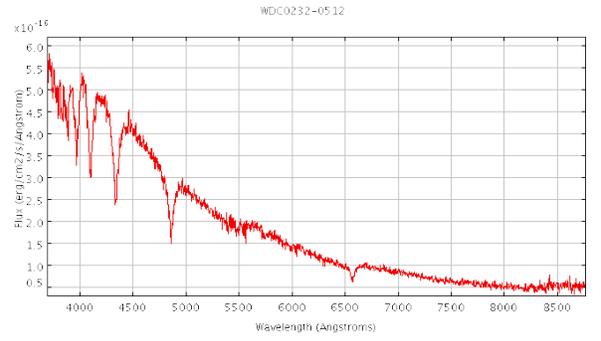
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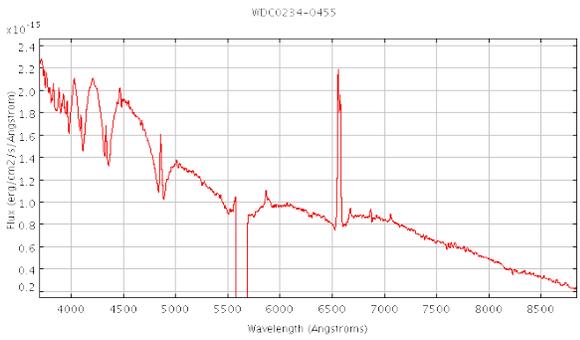
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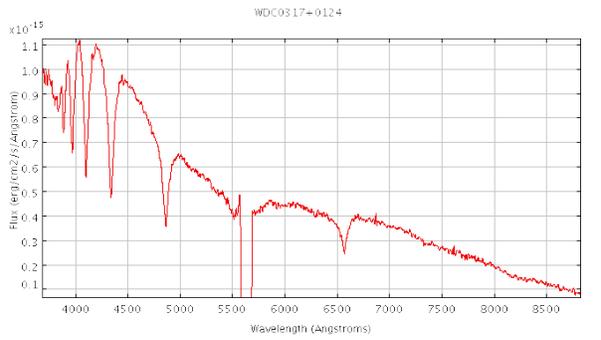
(c) WDC00214-0544



(d) WDC0232-0512



(e) WDC0234-0455



(f) WDC0317+0124

Fig. 3.— Spectra of DA White Dwarfs Found in APO Dataset