The Hertzsprung-Russel Diagram

Introduction

Stars evolve (i.e., change their properties) over millions and often billions of years — too slow for us to see the evolution over human lifespan.[1] Such impressive longevity is due to the fact that stars are powered by thermonuclear reactions, which are very efficient in generating abundant energy and have quite a bit of fuel to last for a long time. Stars like our sun last about 10 billion years (so the Sun is in its middle age). The long timescale of evolution also means that we have to have a different way to study stellar evolution.

Astronomers explore evolution of stars by observing large populations of stars where different stars are in different stages of evolution. Of course, in order to do this we need to be able to tell which star is in what stage. This is done by a combination of observations, which measure luminosity stars and temperatures of their surface, and theoretical models that predict how luminosity and surface temperature change as stars evolve. The key is that luminosity and temperature at a certain age are determined by star's mass, chemical composition, and details of thermonuclear reactions (which elements are burning, over what fraction of star's volume, etc.).

Luminosity and temperature of stars are related because they are both determined by their internal structure, which, in turn, is determined by the controlling parameters (mass, chemical composition, age). Therefore, stars are not scattered randomly in the luminosity and temperature space but follow well defined *sequences* which reflect the ranges of the controlling parameters in a given stellar population.

The surface temperatures of stars can be deduced by fitting a black body radiation spectrum to their spectra. Even for stars that do not have spectra measured, their temperatures can be deduced from their colors (*Question: why color is related to temperature and how? Does bluer color correspond to cooler or hotter temperature?*). Our eyes and brain perceive color by analyzing spectral composition of the incoming light. In astronomy, a star's color is defined as the difference between its magnitudes measured through two different filters that block out all light except light within a fairly narrow range of wavelengths.

In order to measure luminosity of a star, we need to measure its apparent magnitude and distance. The distances can be measured via parallax method for nearby stars, but are difficult to measure accurately for more distant stars. In many cases, one can circumvent this difficulty by studying physical groupings of stars called *stellar clusters,* which are located at the same distance from us and were born at the same time from the same cloud of dense gas.

In this lab you will explore properties of both stars with measured distances and stars in distant stellar clusters. As you will see, stars occupy distinct regions of the observable equivalent of the luminosity-temperature space – the magnitude-color space called *the Hertzsprung-Russell (HR) diagram*[2].

[1] Exceptions are special events in evolution of some stars, such as nova and supernovae bursts.

[2] A nice introduction to the concept and history of the HR diagram can be found at the SDSS Sky Server

The Google Sky basics

In this lab we will be extensively using free software from Google called `Google Earth` – in particular, its part called `Google Sky` (which we will also refer simply as Sky)[3]. Start Google Earth and click on the "Saturn" icon on the top bar, which switches to the Sky portion of Google Earth. Start by learning how to zoom in and out of a given field of view either using the mouse wheel or the zoom tool in the left top corner of the sky map. You can move to different areas of the sky by simply clicking and dragging the sky in the direction you want. Start by zoomin out as much as you can and scanning different parts of the sky. Find the disk of the Milky Way (this is the same band of faint diffuse light you can sometimes see on the sky at a dark site) and scan along it. *Question: what do you notice about the disk? Does it have uniform brightness?* Type "Sagittarius" in the search field at the top left corner and hit enter. The Sky will take you to the constellation Sagittarius.[4] This constellation contains the center of the Milky Way which you can see as one of the brighest regions of the Milky Way band. Scan the sky and try to find two galaxies visible by naked eye in the Southern hemisphere – the Magellanic Clouds. These galaxies are satellites of the Milky Way.[5] We will examine a different, much fainter class of satellite galaxies towards the end of this lab.

Two types of giants and the open clusters

In the search field at the top left corner, type "Orion" and hit enter – the Sky will take you to the region of the Orion constellation with the famous "hunter" shape with the line of three bright stars of the "Orion's belt." Diagonally in the opposite directions from the belt are two very bright stars – Betelgeuse and Rigel – the red(dish) and blue *giants*. These two stars are archetypical examples of the two types of very bright (giant) stars. *Question: what is the main physical difference between these types of stars? In other words, why for comparable luminosity Betelgeuse is reddish while Rigel is blue?*. Just below the Orion's belt, in the "sword region" you can find the famous Orion and Horsehead nebulae – the sites of ongoing star formation from a dense cloud of gas. Zoom in onto the diffuse nebulae and examine the images. You can see dark lanes (one of them is shaped like a head of a horse), where the dust associated with very dense gas is blocking light from background sources, and bright diffuse emission by gas illuminated by recently born stars. You can see some of these blue-colored stars around the nebulae.

Another famous example of a recently born star cluster is the Pleiades. This type of cluster is called an *open cluster* because stars are typically not gravitationally bound to each other and so will leave the cluster after some time. Type "Pleiades" in the search field and hit enter. Examine the bright blue stars of the Pleiades. In this case there are no prominent diffuse nebulae, just a faint haze around bright stars. This is because the cluster is older than

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website: `http://cas.sdss.org/dr4/en/proj/advanced/hr/`

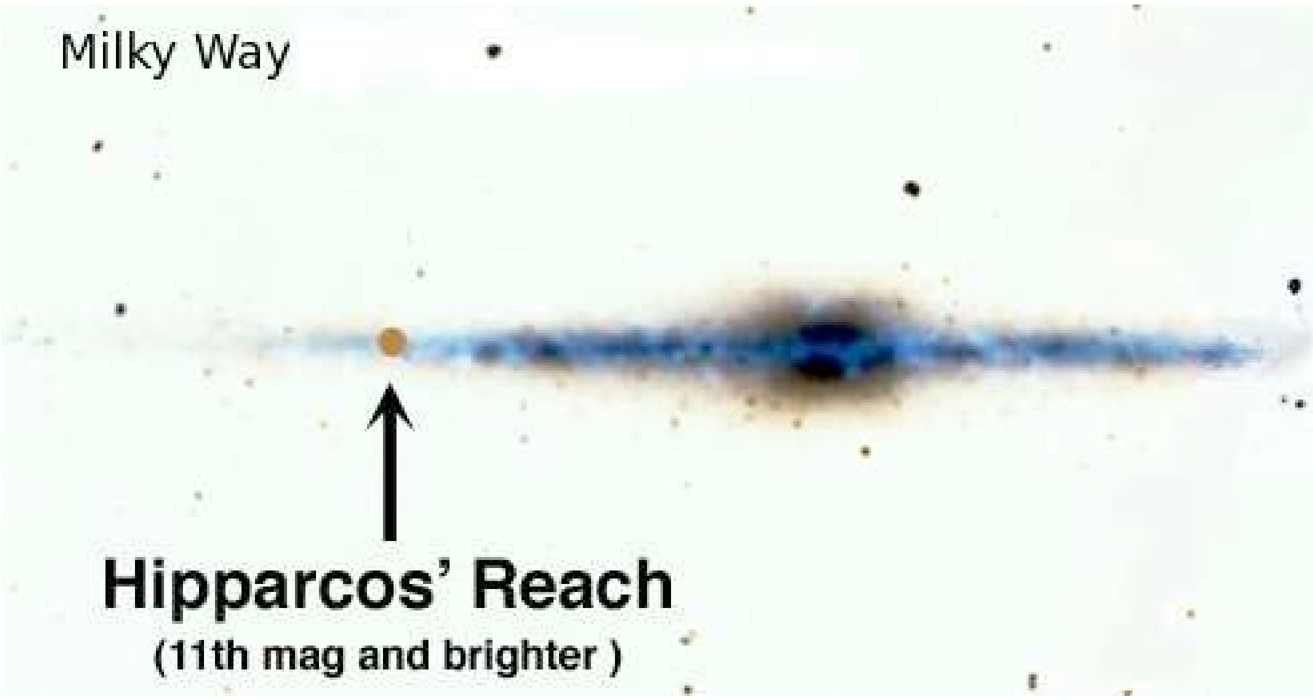
[3]See the description and video introduction to Google Sky at `earth.google.com/sky/skyedu.html`

[4]You can view historical map of the sky with constellations and mythological creatures and figures they are named after by checking "Historical Sky Maps" button in the menu list at the bottom left corner of the Sky window.

[5]Satellite is a smaller galaxy which orbits around a larger galaxy, like a satellite orbits the Earth.

the one in Orion and hot young stars have heated and evaporated most of the remainder of their parent gaseous cloud. You are seeing the cloud in its last stages of disruption.

The light-polluted skies of Chicago are sub-optimal for astronomy (not to mention prone to poor weather). Nevertheless, on a clear night if you go to an open area where you can see a large fraction of the sky you can usually easily find both the Orion constellation and the Pleiades (a small cluster of seven bright stars that stands out) even in Chicago. Try to do this on one of the clear nights in the next two weeks as you are working on this lab. You can use online sky maps[6] to aide you in finding the Orion and Taurus (location of the Pleiades cluster) constellations.



Building an HR Diagram

In this part of the lab you will construct your own HR diagram from the Hipparcos catalog of stars. The purpose of the Hipparcos satellite was to determine the parallax distance to nearby stars. A telescope in space can resolve smaller shifts in astrometric positions of stars compared to a telescope on the ground because the images are not blurred by turbulence in the Earth atmosphere. However, even in space the Hipparcos was able to measure parallax distances to stars only within approximately 200 pc from the Sun (see Figure). The vertical thickness of the stellar disk of the Milky Way is approximately 500 pc. *Question: given this information, do you think stars in the Hipparcos catalog should be distributed on the sky uniformly?*

Turn on the `Hipparcos-Stars` kml script by checking it in the list of "Places" to the left of the main Sky window. You will see star symbols plotted over the sky images where each

[6] e.g., `http://www.stargazing.net/David/constel/skymapindex.html`

star indicates a bright star in the Hipparcos catalog. Zoom out as much as the Sky allows so you can see a large fraction of the sky with a large number of Hipparcos stars. Scan over the sky. *Question: how uniform is distribution of the Hipparcos stars? Can you detect any non-uniformity in their distribution?*

The Hipparcos stars are useful in making the HR diagram for two main reasons: 1) they provide a sample of stars within a given volume, rather than a sample of stars brighter than some apparent magnitude and 2) the measured parallax distances combined with apparent magnitude of the stars give their intrinsic luminosity (or the absolute magnitude). *Question: why these two reasons are important in constructing a representative HR diagram?*

If you click on any of the Hipparcos stars marked when you turn on the plugin, you will get a pop up box with basic information about the star, including its absolute magnitude, spectral type, and BV index (its B-V color). Record absolute magnitudes and B-V colors for $\sim 20-30$ randomly selected Hipparcos stars and plot the stars you recorded on the graph axis in this lab manual.

Lab tasks.

- *Briefly describe distribution of the stars you plotted in the graph.*
- *Label the directions of redder color, and higher temperatures on the x-axis. Label higher luminosity on the y-axis and the location of the most luminous stars (the giants). What kind of colors do the giant stars tend to have?*
- *The abs. magnitude of the Sun in the V-band is 4.8 and its B-V color is 0.63. Mark location of the Sun in the HR diagram. Is the Sun a typical star, from its location on the HR diagram with respect to the other stars? What can you conclude about the kind of nuclear reactions that power the Sun?*

Exploring the HR Diagram of nearby stars

Now zoom out so that you can see hundreds of Hipparcos stars, and turn on the `Hipparcos-HR` plugin. You will see the HR diagram similar to the diagram you just created in the top left corner of the Sky window, but with all the Hipparcos stars in the Sky field of view plotted.

Lab tasks.

- *After you zoom out to a large field of view containing hundreds of the Hipparcos stars, move around the sky and examine the diagram in the top left corner of the Sky window. The diagram draws all the Hipparcos stars that fall into the field of view as you move over the sky automatically. Does the HR diagram change much as you move? Why?*
- *Sketch the main features describing the distribution of stars in the HR diagram.*
- *Brighter stars form two separate sequences. What is the physical explanation for these two sequences in terms of what you know about evolution of stars? What can you tell about the mix of stars in the Hipparcos catalog based on this explanation?*

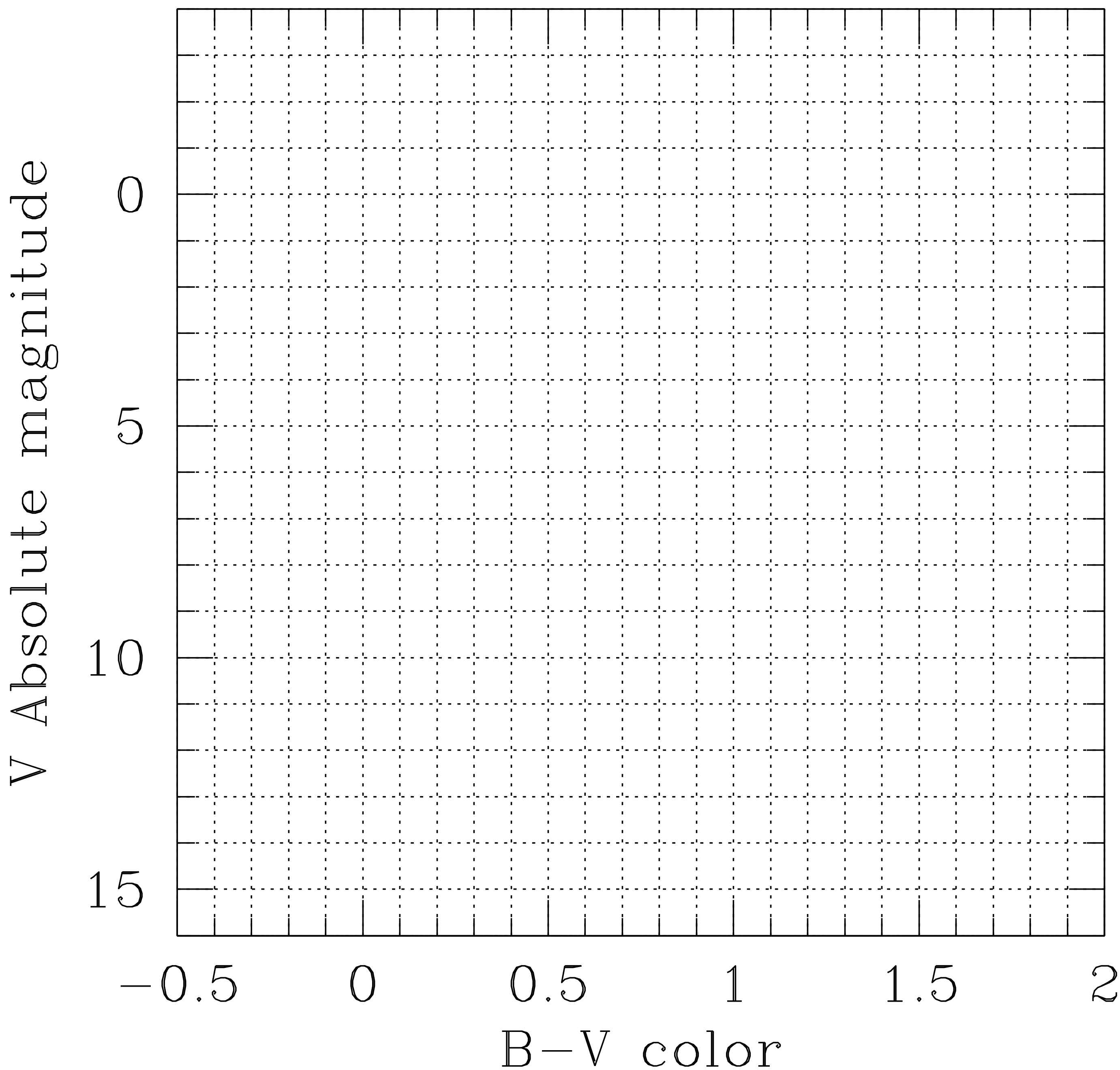


Figure 1: The graph axis for the HR diagram of randomly selected HR stars

- *Note and describe how wide is the main sequence on the diagram in terms of range of colors at a fixed abs. magnitude (this will be used later for comparisons with the HR diagram of stars in clusters). What are the factors that can widen the sequence?*

Hunting for white dwarfs

White dwarfs are a special class of stars which are very blue (almost white) due to the very hot surface temperature (hundreds of thousands of degrees Kelvin), but are very faint because their radius is relatively small (hence the name). They represent the last stages of evolution of some stars (we expect that our Sun will become a white dwarf in another 5-7 billion years). White dwarfs do not have nuclear fusion going on in their interiors anymore and slowly cool. They are sustained by pressure provided by very densely packed electrons in their exterior. Such pressure was predicted on the basis of quantum mechanics and the structure of white dwarfs was first calculated in the 1930s by the late U.Chicago Nobel-winning professor, Subrahmanyan Chandrasekhar. The white dwarfs are visible for a relatively brief period of time after which they cool and fade into obscurity.

You expect to find white dwarfs in the lower left corner of the HR diagram. Scan around the sky and see if you can find the fields in which there are stars in the regions. *Question: how rare are these stars compared to the stars like the Sun? Why?*

HR diagram of the SDSS stars

You are now going to try to characterize clusters of stars using data from the Sloan Digital Sky Survey (SDSS). Deactivate the `Hipparcos-HR` and `Hipparcos-Stars` plugins, pan to the SDSS footprint (you should see 2007 SDSS at the bottom of the Sky window), and zoom in so that you only see a few hundred stars. Activate the `SDSS-star-hr` plugin to plot an HR-diagram of the 1000 brightest SDSS stars in your field of view (you can see which stars are being included in the diagram if you ctivate the `SDSS-star` plugin). SDSS cannot reliably measure parallax to most stars and therefore does not provide parallax distances. Therefore, the y-axis of the diagram in the top left corner is now *apparent* magnitude. Examine a random field in the SDSS area of the sky containing at least a few hundred stars and its HR diagram. *Question: what is different in the distribution of stars in this diagram compared to the HR diagram of the Hipparcos stars? Why is there no distinct main sequence in this case?* (Hint: think of the difference in what's plotted on the y-axis compared to the exercise with the Hipparcos stars).

Examining properties of open clusters

Type NGC 2420 in the search box left of the Sky window and hit enter. The Sky will take you to one of the well known open clusters, with estimated age of 1.7 billion years. Examine the HR diagram plotted for the stars in the field. Zoom in towards the central region of the cluster (grouping of the blue stars) until the scale in the bottom right corner of the Sky window shows size close to $0°03'$ – note the changes in the HR diagram after you zoom in.

Lab tasks.

- *Note the general appearance of the cluster, how compact is it? Are the stars symmetrically distributed around the center?*
- *Describe the differences in the HR diagram of a cluster compared to the random field you examined in the previous exercise (you can sketch distribution of stars in the two cases). Briefly explain why the distribution of stars in the two cases is so different.*
- *How does the HR diagram of stars around the cluster NGC 2420 change after you zoomed in towards its center?*
- *How thick is the main sequence, and how does this compare to the Hipparcos disk stars? Why is this?*
- *At what color (approximately) does the main sequence "turn off" to the right in this cluster?*

Estimating distance to open clusters

Given that inner regions of an open cluster show a tight main sequence of stars, if we assume that these stars are typical for the stars in the disk, we can estimate distance to the cluster. This is done by comparing *apparent* magnitude of a main sequence star of a given color to the absolute magnitude of a main sequence star with known distance. One main sequence star for which we know the luminosity very well is the Sun. The absolute magnitude of the Sun (the apparent magnitude it would have if it was 10 pc away) in the r-band is $M_{r,\odot} = 4.67$ and its $(g-r)$ color is 0.45. Find the apparent magnitude of the main sequence stars of color $(g-r) = 0.45$ in the open cluster NGC 2420, $m_{\rm cluster}$. You can use the *distance modulus*:

$$m - M = 5\log_{10}(d/10\,{\rm pc}) = -5 + 5\log_{10} d, \quad (1)$$

where d is in parsecs, to calculate the distance to the cluster as

$$d_{\rm cluster} = 10^{0.2(m_{\rm cluster} - M_{r,\odot} + 5)}. \quad (2)$$

In reality this distance is a bit of an overestimate, as it does not take into account effects of interstellar dust which makes the stars appear fainter and colors somewhat redder than they actuall are. It also does not take into account the fact that stars in this cluster have smaller fraction of heavier elements that the Sun, which would shift the location of the main sequence.

In astronomy we are always wary of making conclusions about a class of objects based on observation of a single system. Type NGC 2266 in the search box and hit enter. You will be taken to another open stellar cluster. Zoom in to the central region of the cluster until you have about 100 or so stars in the field of view. At what distance is this cluster located? Can you see a "turn off" in its main sequence? What does it tell you about the age of this cluster relative to NGC 2420? Repeat the exercise and answer the same questions about cluster NGC 6791 (you will need to zoom in deep into the center of this cluster to see its main sequence clearly).

Examining properties of globular clusters

Globular clusters are stellar clusters of a different type. There are several big differences between the globular and open clusters: 1) globular clusters tend to contain more stars (the largest ones contain over a million stars); 2) they are more deficient in heavy elements and are significantly older (ages $> 8-12$ billion years); 3) spatial distribution of globular clusters is close to spherical about the center of the Milky Way, while open clusters are found in the disk plane or close to it. These differences are due to the fact that the two types of clusters correspond to two different populations of stars in our Galaxy: disk population I (open clusters) and halo population II (globular clusters).

There are many globular clusters in the Messier catalog. Type M5 in the search box and hit enter. The Sky will take you to one of the spectacular globular clusters containing about half a million of stars. SDSS measured properties of some of the stars in the outer regions of the cluster. Examine the HR diagram plotted for these stars. Some other good examples of the globular clusters you should examine are M3 and M13

Lab tasks.

- *Note the general appearance of the globular clusters. Describe the differences in the visual appearance between open and globular clusters.*

- *How are the HR diagrams of globular clusters differ from those of the open clusters? Stars in which evolutionary stages can you see in the HR diagrams of globular clusters?*

- *Estimate approximate distances to the globular clusters using the same method as before for the open clusters (you may need to zoom in close to the cluster center so that the plotted diagram is extended to sufficiently faint stars). How do the distances compare to those you obtained for the open clusters? How you can interpret the difference in distance in terms of the structure of our Galaxy (i.e., spatial distribution of different stellar populations)?*

- *Stellar evolution models predict that cluster age can be estimated by the difference in magnitudes between the stars on the "horizonthal branch" sequence of the HR diagram and the magnitude of the main sequence "turn off" with larger magnitude difference indicating older age of stellar population. Examine HR diagrams of globular clusters M3 and M5; which cluster is older?*

The faintest dwarf galaxies in the universe and the HR diagram

To end this lab, you will examine one of the faintest galaxies in the universe. First, turn off the SDSS color-magnitude plugin. Then, in the "Location search" field to the left of the top left corner of the Sky window type coordinates `57.9153 80.0516` and type enter. Examine the stellar field you see. Believe it or not, but you are looking at a galaxy. This galaxy in the constellation of Draco does not look anything like spectacular luminous galaxies you have seen in pictures before; it is a very faint galaxy of the *dwarf spheroidal* class, a satellite of the Milky Way. These galaxies were discovered relatively recently due to their extreme faintness and are in fact impossible to see with the modern telescopes beyond the Milky Way halo.

How can we tell that there is a galaxy here at all? This is where the HR diagram is very useful. If you turn on the SDSS color-magnitude plugin again, you will see that the distribution of stars in the diagram is not random (compare it to the random field you examined previously in the lab or simply look at how HR diagram changes when you move away from the location of the galaxy). Even though it is hard to discern small concentration of stars in the general stellar field, the stars belonging to the galaxy are at approximately the same distance from us and therefore cluster in regions corresponding to the evolutionary stages of its stars. The foreground and background stars, on the other hand, are located at different distances from us and are scattered much more randomly in the HR diagram. Astronomers thus search for such galaxies by searching the sky for fields with distinct concentrations of stars in sequences in the HR diagram.

Lab tasks.

- *How do you interpret the sequences stars form in the field of the Draco dwarf galaxy? What stellar evolution stages do they represent?*
- *Identify the sequences similar to those you saw in the HR diagrams of globular clusters. How does the thickness of these features (spread in color at a given apparent magnitude) compare to those of the globular clusters? How can you explain the difference?*
- *Based on the apparent magnitudes of the "horizonthal branch" of stars how far away do you think is this galaxy compared to the globular clusters you examined before?*