MASARYKOVA UNIVERZITA
PŘÍRODOVĚDECKÁ FAKULTA
ÚSTAV TEORETICKÉ FYZIKY A ASTROFYZIKY

Bakalářská práce

BRNO 2015 MARTIN PIECKA

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Metody určování hustoty mezihvězdného prostředí

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Vedoucí práce: doc. Mgr. Ernst Paunzen, Dr. **Brno 2015**

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Autor:	Martin Piecka Přírodovědecká fakulta, Masarykova univerzita Ústav teoretické fyziky a astrofyziky
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Abstrakt

V této bakalářské práci se věnujeme studiu mezihvězdého prostředí v okolí Sluneční soustavy. Difúzní mezihvězdná pásma představují soubory neznámych spektrálních čár, které je nutno identifikovat pro určení hustoty mezihvězdné látky.

V teoretické části se věnujeme spektrálním čárám a historii výzkumu difúzních pásem. Praktická část je zaměřená na studium souvislostí mezi vybranými pásmy a mezihvězdnou extinkci v různých směrech pozorování.

Abstract

In this thesis we study the interstellar medium around our Solar System. Diffuse interstellar bands are mysterious groups of spectral lines which need to be identified before being able to determine the density of the interstellar medium medium.

In theoretical part of this work we aim to study spectral lines and the history of research of the bands. Practical part is focused on exploring the relations between the chosen bands and interstellar extinction in the different lines of sight.

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The knowledge about the density of the interstellar medium is very important to put constraints on the stellar formation and the different extinction laws. There are different methods developed to estimate the densities in different line of sights and distances from the Sun. The results of these methods should be compared and analysed.

Literatura:
DYSON, John Edward a David Arnold WILLIAMS. *The physics of the interstellar medium*. 2nd ed. Bristol: Institute of Physics Publishing, 1997. xiv, 165 s. ISBN 0-7503-0460-X.

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Prohlášení

Prohlašuji, že jsem svoji bakalářskou práci vypracoval samostatně s využitím informačních zdrojů, které jsou v práci citovány.

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Martin Piecka

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Introduction

Determination of the density of the interstellar medium is an important goal of modern astrophysics since it has a direct impact on our view of the universe. Many atoms and molecules have already been discovered since spectroscopical methods were developed. This changed our understanding of the space and terms like interstellar and intergalactic medium started to be used. The medium adds to the overall mass of the galaxies and the density of the universe, knowledge of which is critically important in cosmology. It is the interstellar medium which causes the light extinction, the absorption of photons, and due to this fact, astronomers were able to corrent distances in our Galaxy.

Although our space is known to be filled mostly with hydrogen and helium, other elements and many more molecules are also present and just as important. For instance, metallicity of stars may show us something about current generation of stars, how they are formed and what kind of life we may expect from them. If our universe was filled with relatively much higher amount of heavier material, conditions for creation of stars as well as light extinction would change. It is important to point out that extinction sets limits to the possibilities of our observations. Since we expect that only lighter elements where formed in the early stages of the universe, heavier elements are thought to be formed in stars. This shows us how important it is to know the structure of our universe and the distribution of the material in it because it corresponds to the evolution of the universe itself and galaxies, stars and planets in it as well.

Diffuse interstellar bands (DIBs) are absorption features found in the lines of sight of stars and other astronomical objects separated from us by interstellar medium. They represent a great mistery and challenge in spectroscopic research because there has not been any common source of these features identified and only few of the given features have been associated with laboratory experiments. There are several hundred DIBs confirmed and they can mostly be seen in near ultraviolet, visible and near infrared parts of the spectrum. The field of the universe research is really vast and complex challenge for many human generations and investigation of DIBs also represents the source of many unanswered questions, the answers of which are based on the years of research and observations, and therefore, the given work is mainly focused only on some of the most observed DIBs.

Chapter 1

Interstellar Medium

One of the most important components of the galaxies is the interstellar medium (ISM). It is responsible for the creation of the stars and also holds an important role in the change of the energy of the galaxies. ISM may be found in a form of baryonic matter as an interstellar gas and dust, cosmic rays and even the photons between stars are part of it as well. Including gravitational field, force fields are also part of the ISM as well as the dark matter which stands for the most of the mass of the galaxies. However, baryonic matter also represents a smaller contribution to the mass, and since we cannot research dark matter, it is the interstellar gas and dust that has been explored mostly. This form of matter determines the formation of the stars and emission of the energy from galaxies while infall of the gas from the intergalactic medium adds to the amount of the matter in them.

Most of the gas and dust is concentrated into a disk with estimated thickness of several hundred pc and compared with, for example, the approximate distance of 8.5 kpc of the Sun from the centre of the Galaxy, it may be considered as a thin disk. It is this part of the galaxies that we are most interested in. Since the interstellar medium contains regions with various temperatures and densities, it would be convenient to define some characteristic phases that account for the most of the mass and the volume of the ISM in our Galaxy.

1.1 Characteristic Phases

1.1.1 Coronal Gas

This gas, which may also be called a hot ionized medium, is typically heated to high temperatures of $\sim$ 100 000 K by supernovae. It is ionized by collisions with the particles of the blastwave and occupies a large volume of our Galaxy, and therefore, has only a very low density. It is being cooled by the Röntgen emission and adiabatic expansion over the time of millions of years. This part of the interstellar medium may be observed in UV and X-Ray emission and radio synchrotron emission.

1.1.2 H II Gas

We can divide this gas into a dense H II regions and diffuse H II. The gas is photoionized by ultraviolet radiation of the hot and massive O-type stars. H II regions usually have dimensions of a few pc and high temperatures and due to their high densities, they offer the perfect conditions for star formation. Their existence is connected with the ionizing stars, giving them a lifetime of several millions of years. Diffuse photoionized regions, or warm ionized medium, however contain the mass of about a billion of Suns which is much more than in the case of dense H II regions. Ionized hydrogen gas is mostly cooled by optical line emission, fine-structure line emission or by free-free radiation, a deceleration of charged particles in plasma. Warm ionized medium is observed mostly in H α emission line.

1.1.3 H I Gas

This gas contains hydrogen mostly in atomic form. Its properties depend on its temperature and thus, it can be differentiated into a warm (WNM) and a cool neutral medium (CNM). Warm neutral medium has a temperature of thousands of kelvins and gets heated by photoelectrons from dust. With the density of 0.6 hydrogen atoms per cubic centimetre, it fills a large part of the volume of our galactic disk. Cool H I gas has greater densities but lower temperature of $\sim$ 100 K. Both phases can be observed by tracing 21 cm absorption (CNM) or emission (WNM) line. Cooling of the H I gas has a form of fine-structure line emission or optical emission in the warm neutral medium.

1.1.4 H_2 Gas

Molecular hydrogen clouds are gravitationally bound. Diffuse H_2 gas can be found in temperature of about 50 K but with greater density in comparison with cool neutral

Figure 1.1: The Horsehead Nebula is a molecular cloud located in the constellation Orion. Image was created by Kitt Peak National Observatory on December 28th in 1994. (Taken from: `https://www.noao.edu/image_gallery/html/im0057.html`).

medium, so that H_2 molecule may be present in greater numbers inside of the cloud. Dense H_2 gas has the densities in the range of several thousand to a million of hydrogen atoms per cubic centimetre. Typical temperatures of those clouds are just over 10 K. H_2 clouds are generally observed in CO 2.6 mm emission and it is also connected with their cooling.

1.1.5 Cool Stellar Outflows

With mass loss rates of 10^{-4} solar masses per year and outflow velocities below 30 km/s, evolved cool stars create dense stellar outflows while hotter stars create outflows with greater temperature and velocity but lower density. Stellar outflows therefore vary and may have temperatures in range 10 - 1000 K and densities up to millions of atoms of hydrogen per cubic centimetre. Observations are carried out on the basis of optical and UV absorption, dust IR and H I, CO, OH radio emission, depending on the character of the outflow.

1.2 Processes

Within the clouds of interstellar gas, several processes dominate when it comes to change of their properties. Temperature is possibly the most important one, due to the fact that it usually helps us to determine other quantities, including density. It is therefore critically important to understand the processes of molecular formation, cooling and heating of the gas, since they determine the temperature of the medium.

1.2.1 Heating

Interstellar clouds are usually heated by starlight, cosmic rays, stellar winds or supernovae. Although very potent, the last mentioned source of energy occurs only very rarely. Supernovae and novae however have the most significant impact on the medium because they change its distribution and properties in the most dramatic way. They usually occur when massive stars reach the final phase of their evolution or when the matter transition from a star of a binary system to its companion, a white dwarf, reaches the critical point at which the material bursts into explosion.

Starlight is another important source of energy for heating the interstellar gas. When photoionization occurs, the concerning electron loses its bond with the atom and becomes a free particle with kinetic energy of the difference between the energy of the photon and ionization potential. With photon being absorbed by the atom, the free electron may now collide with other atoms and particles of the cloud and increase its temperature. Although the free electrons may recombine with ions created in the gas and lose this energy, the heating usually dominates in clouds with lower temperatures. Photodissociation of molecular hydrogen also leads to the heating, when two atoms of hydrogen are left with kinetic energy which they share with the rest of the cloud. The amount of heat created by the photodissociation depends on the frequency of molecular break-down and formation.

High-energy protons and electrons are also a source of heat. When colliding with hydrogen atoms, they ionize them, causing them to emit a free electron which shares its energy with neutral medium, causing further ionization and excitation resulting in the emission of photon which leaves the cloud. Therefore, only elastic collisions lead to the generation of heat within the cloud and they occur mostly when the free electron collides with ionized particles, for example, the hydrogen of the H II gas. If electrons collide with molecular hydrogen and the collision is not elastic, the molecule becomes excited and may be a source of ultraviolet radiation, causing further dissociation, especially in dense clouds.

The planetary nebulae are very intriguing objects. They are created by stellar wind with the help of ultraviolet radiation of the stars with lower masses that at the end of their life on the main sequence become red giants and lose a great part of their atmospheres. The ejected material then collides with nearby interstellar medium, causing its temperature to rise.

In the diffuse neutral clouds, one of the most important heating processes is thought to be the photoelectric effect caused by the interstellar grains. Let us say that the grain has a work function W and that the energy of absorbed UV photon is hf, then the energy of emitted electron would be equal to their difference with this free particle becoming a source of energy for the cloud.

1.2.2 Cooling

Since the interstellar medium is usually not dense enough to conduct heat quickly, the main mechanism of cooling is the emission of radiation. Emission occurs when an atom or a molecule collides with another particle and gains part of its kinetic energy. If the energy gained by the collision is sufficient enough, electron in the atom moves into a higher energy state. The excitation lasts for a short period of time, after which a photon is radiated with energy equal to the difference between the energy state before and after the emission. The loss of energy is therefore mostly equal to the amount of energy carried by photons which escape the cloud. This cooling mechanism is, however, efficient only if the frequency of collisions is very high and if the thermal kinetic energy of the cloud is higher than the excitation energy of the atom or molecule which is to be excited. It is also important for the cloud to be optically thin in the cooling radiation, so that the photons emitted by this process are not re-absorbed.

As mentioned above, the effectiveness of cooling of the medium is determined by the frequency of collisions. The frequency itself, when considering only the inner structure of the medium, depends mainly on the abundance of present material. Let us first consider only atoms and their ions. Most abundant are H, C, N and O. In many regions of the interstellar medium, the present carbon is in a form of C^+. Considering a transition $^2P_{1/2} \rightarrow {}^2P_{3/2}$, when the difference between the energy of the states is approximately equal to 92 K, the cooling by this emission will be important if the temperature of the cloud is around 100 K. To determine the cooling rate, it is needed to know the collisional excitation cross-section as a function of temperature. For the collisions of C^+ with their colliding partners electrons, the relation between the cooling rate and the temperature of the gas, while considering the Maxwellian distribution of velocities, is

$$A(C^+) = n(e)\, n(C^+)\, 8 \times 10^{-33}\, T^{-1/2}\, e^{-92[K]/T} \,. \tag{1.1}$$

Hydrogen is the most abundant of all atoms in the interstellar medium and many would expect it to dominate in the process of cooling, but as it has been seen, the temperature required for the excitation plays a key role in the effectiveness of the cooling by given atom. For hydrogen, the energy difference between the first state and second excitation state is over 20000 K, so a very high temperature of the cloud would be required for this process to be important.

In many clouds, H_2 is a very abundant molecule. Due to its rotation, it produces a spectrum of lines, and has energies given by a following relation

$$E_J = BJ(J+1) \text{ and } J = 0,1,2,\dots, \tag{1.2}$$

where B is the rotational constant which depends on the inertia momentum of the molecule. For molecular hydrogen, there is no dipole moment in these states and the transitions therefore occur by electric quadrupole interaction ($\Delta J = \pm 2$). The least energetic transition in H_2 is $0 \to 2$ and it occurs at the temperature of 510 K. The process of cooling by molecules differs from the one caused by atoms because, for example, the lifetime of the rotational level $J = 2$ are hundreds of years, which is long time in comparison with the frequency of collisions. This form of cooling is therefore ineffective. This does not apply to hydrogen deuteride (HD), which has a small dipole moment and transitions $\Delta J = \pm 1$ are allowed, meaning that cooling per molecule by HD is more effective than by H_2. It however loses its significance due to its low abundance in comparison with H_2 (there are over 10^5 H_2 for each HD molecule). Estimated cooling rate for H_2 is

$$A(H_2) = \sum_{J\geq 1} n(H_2, J)\,\Delta E(J \to J-2)A(J \to J-2), \tag{1.3}$$

which, for example, gives a value of 10^{-33} J/s per molecule at $T = 100$ K.

Molecule CO represents one of very important coolants and is the second most abundant molecule in the interstellar medium. It possesses a dipole moment, allowing rotational transitions between the lowest CO energy levels $J = 0$ and $J = 1$. The energy difference between those two states is around 5.5 K, making CO a very important coolant in the clouds at low temperatures. The efficiency of this cooling may be considerably reduced in the dense clouds with high column CO density, where this molecule becomes an absorber of its photons. Other molecules, like OH or H_2O, are also very important in the process of cooling of the medium.

1.2.3 Formation of Molecules

The presence of molecules in the interstellar medium changes its properties (for example, the total cooling rate) and therefore, it is important to understand the process of their formation. Interaction between two atoms A and B may result in the creation of a molecule C, but this is very unlikely. The collision between these two atoms will be elastic, if no energy is removed. One way of taking the energy from the colliding pair is to radiate energy away during the collision which however lasts for only a short period of time, meaning that only a very small amount of these collisions will form a molecule - this process is called radiative association. It is also possible to remove part of the energy by a third particle, but this is again very unlikely to happen in the interstellar medium because of its low density. In addition, the environment conditions (e.g. UV radiation) may cause the destruction of some present molecules and it, on the other hand, increases the abundance of other molecules which are a result of such photodissociation. For molecules to have a high enough rate of formation to be present in the medium, processes with large cross-sections are required. Increasing the time of collisions also increases the probability of molecular formation (for example, catalysis at the surface of dust grains).

If we start to think about chemical reactions between molecules instead of radiative association of atoms A and B mentioned above, then the energy stabilization ceases to be a problem, since the additional energy may appear in a form of kinetic energy. Very fast reactions occur between ions and molecules. This is due to the fact that the presence of ion induces an electric dipole in the molecule and increases the cross-section value. Exothermic reactions in the medium between neutral atoms and molecules also occur. Neutral atom replaces an atom in the molecule and the rearrangement happens in such a way that the molecule produced by the reaction has the strongest bond between the two atoms. For example, the collision between CH and O produces CO and H because the bond in CH is weaker than in CO. Forces between the molecules and neutral atoms are weak and this means that the cross-section will be smaller in comparison with the reactions between molecules and ions.

In many cases, the reactions depend on the presence of H_2. Since the UV radiation destroys these molecules and they cannot be formed by radiative association, a question rises about their origin. Most embraced theory is that H_2 is catalysed on the surface of the grains.

1.3 Interstellar Grains

When exploring the light extinction, astronomers found that the average interstellar extinction curve, which shows the relation between the extinction and wavelength, has strange unexpected features, for example 220 nm peak. It was thought to be caused by small solid particles. Their presence in the interstellar medium was, however, confirmed after the discovery of starlight polarization which could only be explained by a presence of dust grains. The existence of polarization requires grains to be elongated (not spherical) and they have to be to some degree aligned. One possible alignment mechanism is explained if we assume that grains are paramagnetic and placed in an interstellar medium which contains a magnetic field. The problem of randomly rotating grains is solved because the magnetic field induces a magnetic moment and damps the rotation of the molecule. Another way to prove the presence of the grains is the diffuse light which is not directed from any particular source. It can, however, be explained if we assume a presence of grains in the interstellar medium, causing the scattering of the light, since atoms and molecules could not cause such an effect.

In order to understand, how the interstellar grains affect the surrounding gas, knowledge of several properties is required, including shape and size distribution or the composition of the grains. By observing extinction in UV as well as scattering of the light and polarization, it can be showed that the grains are mostly of size between 0.01 μm and 0.2 μm, but their size is not constrained in this range. Most of the mass of the dust is in large grains while smaller grains contribute to most of the surface area.

Although the energy absorbed by grains is mostly emitted back in IR, observations of reflection nebulae also show light in optical and near-IR part of the spectrum. This is called luminescence of the grains and is probably caused by the absorption of photons with higher frequencies by material which so far has not been identified. However, small knowledge of the interstellar dust we have, its presence is obvious and very important in the evolution of planets and galaxies.

1.4 Spectral Lines

Most of our knowledge about the stars, interstellar medium, or even the whole universe, comes from the studies of the observed electromagnetic radiation. When we look at the spectrum of, for example, stars, we will notice that the spectrum has a couple of characteristic features. One of them is a spectral line which is a very narrow band of frequencies and it arises when a molecule or an atom absorbs or emits a photon with its energy equal to excitation energy. Another feature is a continuous emission (or absorption) which is present in the spectrum due to the ionization by a photon with energy higher than the ground state energy. Depending on whether the intensity of the band in the spectrum is higher or lower than the intensity of the light with higher and lower frequencies, we can distinguish between absorption or emission bands.

Since the lines are not infinitely thin, but rather a narrow or even wide bands, they have characteristic shapes, which may give us the information about the carrier of the line. They can also be identified by the wavelength of the photons, if corrected for reddening. Understanding the shapes and knowing the energy states of atoms and molecules, therefore, helps us to find the carriers, giving us the knowledge about the structure of the universe.

1.4.1 Shapes

A very basic form of line shape is called Lorentzian profile (Lorentzian). To find the relation between the intensity and the frequency of the electromagnetic radiation, we regard the emitting atom as an oscillator which is lightly damped by a force $\boldsymbol{F}$. If the position of the oscillator is given by vector $\boldsymbol{r}$, the system could be described by the equation of motion:

$$m\ddot{\boldsymbol{r}} = -m\,{\omega_0}^2\boldsymbol{r} + \boldsymbol{F}\,, \tag{1.4}$$

$$\ddot{\boldsymbol{r}} = -{\omega_0}^2\boldsymbol{r} - y\dot{\boldsymbol{r}}\,. \tag{1.5}$$

Since we expect only a small damping $y << \omega_0$, we can find a solution of the differential equation:

$$\boldsymbol{r}(t) = \boldsymbol{r}_0\,\mathrm{e}^{-yt/2}\,\mathrm{e}^{-i\,\omega_0\,t} \tag{1.6}$$

and similarly for the electric field

$$\boldsymbol{E}(t) = \boldsymbol{E}_0\,\mathrm{e}^{-yt/2}\,\mathrm{e}^{-i\,\omega_0\,t}\,. \tag{1.7}$$

Decomposing this function into frequencies with the help of Fourier transform, we get

$$\dot{\boldsymbol{E}}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{+\infty}\boldsymbol{E}(t)\,\mathrm{e}^{i\,\omega\,t}\mathrm{d}t = \frac{1}{2\pi}\,\frac{\boldsymbol{E}_0}{i\,(\omega-\omega_0)-y/2}\,. \tag{1.8}$$

Stating that the intensity of the radiation $I(f)$ is equal to $\dot{\boldsymbol{E}}^2$ and that radial frequency can be written in terms of frequency $f = \omega/2\pi$, we get the relation between intensity and frequency

$$I(f) \sim \frac{1}{(f-f_0)^2 + (y/4\pi)^2}, \tag{1.9}$$

where we can see that the maximum of intensity is at $f = f_0$ and that the line is actually a band of frequencies.

Since, however, the atoms in the interstellar medium have random velocities, with respect to us as observers, the Doppler broadening affects the actual profile of the line. Broadening may also be caused by the relative motion of the cloud with respect to the observer. The equation for the shift in frequencies caused by the relative velocity of the atom is

$$\frac{f-f_0}{f_0} = \frac{v}{c}, \tag{1.10}$$

and if the velocity distribution is Maxwellian, then we can find the intensity-frequency relation by integrating

$$\mathrm{d}I \sim \mathrm{e}^{-\frac{Mv^2}{2kT}}\mathrm{d}v, \tag{1.11}$$

$$I \sim \mathrm{e}^{-\frac{(f-f_0)^2}{2\delta^2}}, \tag{1.12}$$

yielding the radiation intensity along the way towards the observer. This shape is called Doppler curve or Gaussian. Once again, we find that the maximum is at $f = f_0$. If we compare these two profiles with normalized intensity, considering that the area underneath is unity, we find that Gaussian has, in comparison with Lorentzian, higher intensity at maximum and less wide frequency band.

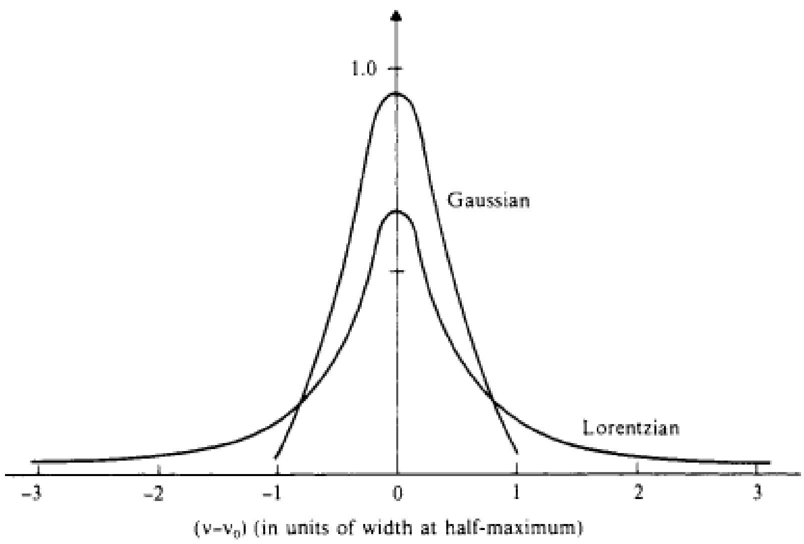


Figure 1.2: Comparison of Gaussian and Lorentzian normalized line shapes with area under both being unity. Shapes have the same width at half of their maximum intensity. Image taken from the second edition of the textbook *Physics of the Interstellar Medium* by Dyson and Williams.

1.4.2 Measurement

When observing an absorption line, it is clear that its profile is more complicated than stated above. It is due to the fact that the profile is actually a combination of Gaussians and a Lorentzian. To characterise a line, it is more convenient to measure less complex quantities, such as equivalent width. Its value can be found by calculating the area inside the line and creating a rectangle with the height defined from zero to continuum intensity - the equivalent width is then a width of such rectangle which has the same area as the line inside

$$W = \int \frac{1 - I(f)}{I_{0,f}} \, \mathrm{d}f \,. \tag{1.13}$$

The intensity of radiation is given by the amount of absorption along the path from the source. The relation between the measured intensity and initial intensity I_0 is

$$I(f) = I_{0,f} \, \mathrm{e}^{-\tau_f} \,. \tag{1.14}$$

Quantity τ_f is called an optical depth and is given by absorption coefficient $\kappa(f)$ (which depends on the cross section and particle column density) and the distance between the source and the observer

$$\tau_f = \int \kappa(f) \, \mathrm{d}s = \int n \, \sigma_f \, \mathrm{d}s \,. \tag{1.15}$$

Putting equations (1.13) and (1.14) together, we get

$$W = \int 1 - \mathrm{e}^{-\tau_f} \, \mathrm{d}f \,. \tag{1.16}$$

In optically thin case we have only a very small value of $\tau_f << 1$, so the equation takes a more simple form

$$W = \int \tau_f \, \mathrm{d}f = N \int \sigma_f \, \mathrm{d}f = N \, \sigma_0 \, \Delta f \,. \tag{1.17}$$

This equation introduces the mean cross section value σ_0 which is averaged over Δf. We can see from the equation that if we know this value and calculate the area of the line, we can (in optically thin case) directly measure the particle column density.

It is sometimes necessary to consider the angular size of the radiation. In this case, the equation for the observed intensity is more complicated - another component appears on the right side of the equation which depends on the optical depth. Let us assume that the absorbing material is in thermodynamical equilibrium and that the radiation comes from a black body with intensity defined by Planck's law

$$B_f(T) = \frac{2hf^3}{c^2} \frac{1}{\mathrm{e}^{hf/kT} - 1} \,, \tag{1.18}$$

and the equation for intensity takes a form

$$I = I_{0,f} \, \mathrm{e}^{-\tau_f} + B_f(T) \, (1 - \mathrm{e}^{-\tau_f}) \,. \tag{1.19}$$

By combining equations (1.13) and (1.19) again, we get the relation between the intensity of radiation and equivalent width

$$W = \int 1 - e^{-\tau_f} + \frac{B_f(t)}{I_{0,f}} (1 - e^{-\tau_f})\, df\,, \tag{1.20}$$

$$W = \int \tau_f \frac{1 + B_f(T)}{I_0, f}\, df \;\; \text{(in optically thin case)}\,, \tag{1.21}$$

and we can see that it differs by the ratio of intensities given by the temperature which causes the black body radiation.

1.4.3 Carriers

The interstellar lines are formed when the carrier of the lines changes its energy level by a process. In the regions, where gas is ionized by a hot star, we observe ions producing lines from metastable states. Also, we can sometimes see the same line multiple times. This is caused by Doppler effect, when we observe multiple clouds with different velocities at the same time. As we can see, there are many ways how even the same atom may produce lines. When new lines are discovered, it is important to consider many effects in order to find the real carrier of the line and the situation is even more complicated when considering more complex organic molecules.

Neutral atomic hydrogen produces 21 cm line in radio part of the spectrum. Since proton and electron have spin 1/2 and the orbital angular momentum in the ground state is zero, the total spin can only have the value 1 or 0. The line at 21 cm is produced when the transition between these states occurs. Observing this line provides us many information about the interstellar medium. For example, the line is usually associated with the optically thin case emission and we can easily find the density of hydrogen towards the source. Also, broadening of the line is relatively small and we can, therefore, distinguish between clouds with different velocities. There are many more lines associated with hydrogen atom. Another example would represented by H α, a spectral line which is responsible for the red colour of clouds we observe. This line is produced by a recombination of hydrogen ion and electron, a process, which can be described by the change from state $n = 3$ to the state $n = 2$:

$$E = \frac{hc}{\lambda} = 13.6 \left(\frac{1}{2^2} - \frac{1}{3^2} \right) \mathrm{eV} \;\Rightarrow\; \lambda \sim 656\ \mathrm{nm}\,. \tag{1.22}$$

Molecules are however more frequently found in the spectrum and they are the most valuable source of information about the regions containing most mass. Molecular lines are mostly located in the radio part of the spectrum. They are usually produced with other lines and form so called rotational spectra. The molecule cannot rotate arbitrarily, but the rotation is restricted to the energy states given by

$$E = BJ(J+1) \;\; \text{and} \;\; J = 0, 1, 2, \ldots\,, \tag{1.23}$$

where constant B is related to the moment of inertia by the equation

$$B = \frac{h^2}{8\pi^2 I}\,, \tag{1.24}$$

and J is rotational quantum number. This is a quantum mechanical equation for rigid rotator and it can be applied for linear and diatomic molecules. The selection rule for the transitions is $\Delta J = \pm 1$ and that means that for heavier and larger molecules, the energy levels are close together and the transitions, therefore, produce photons with long wavelengths. For example, the molecule CO, which is the second most abundant molecule observed, produces 2.6 mm photon by transition $J = 1 \rightarrow J = 0$.

The equation is more complicated for polyatomic molecules which are usually not linear. A molecule is called symmetric-top if two of its principal moments of inertia are the same. In this case, two quantum numbers are required to describe the energy levels - J for the total angular momentum and K for the projection of the total angular momentum on the axis of symmetry

$$B = \frac{h^2}{8\pi^2 I_B}\,, \;\; A = \frac{h^2}{8\pi^2 I_A}\,, \tag{1.25}$$

$$E = BJ(J+1) + (A-B)K^2\,, \tag{1.26}$$

where J is defined as previously and

$$K = -J, -J+1, ..., J-1, J\,. \tag{1.27}$$

Asymmetric-top molecules with all principal moments of inertia being different have a very complicated motion which cannot be described by a simple equation like (1.23) and (1.26). It is however possible to find energy levels using numerical methods and in theory, even to assign the line to the correct carrier. An example of such molecule would be H_2O, which produces rich and complicated spectrum of lines.

Chapter 2

Diffuse Interstellar Bands

At present, spectroscopy is one of the most useful research methods for understanding the known universe. By looking at the spectra of stars, one may find different spectral lines which may say a lot about the stars, interstellar medium and other objects. Beside known lines, we can identify other not very well understood features. Diffuse interstellar bands are one of them and they represent a great mystery, since almost none of them were identified. So far, almost every research ever made about the carriers of the bands was mostly inconclusive. Each time an article about this phenomenon is published, it provides only little new information and even at present, we know little about DIBs. To find better understanding about what we are dealing with, we shall take a closer look at the early history of the research, the techniques used in the search for the carriers and we will try to interpret information from some articles.

2.1 A Brief History

First astronomer who reported an observation of these strange absorption features was Mary L. Heger in 1919. Not much of research has been done until 1933, when Paul W. Merrill published an article, where he referred to the fact that lines 5780 Å, 5797 Å, 6284 Å and 6614 Å were not affected by Doppler effect of the observed binary star with significant variation of radial velocity and therefore, he stated that they are most likely to be of interstellar origin. He also noticed that intensities of mentioned lines were increasing with the distance of the stars, supporting the notion of the source of the lines being interstellar. A year later, Pol Swings pointed out, that the newfound mysterious lines in the visible part of the spectrum were much broader than expected and had diffuse edges. Thus, the designation ”Diffuse Interstellar Bands”came to existence several years later.

W. P. Merrill and O. C. Wilson came up with three possibilities of the origin of unidentified lines. The first one was that they could be atomic lines. Finding this to be very unlikely, they began to think that these absorption features may actually be of molecular origin. Looking at the suggestions of carbon dioxide (P. Swings, 1937) and molecular sodium (M. N. Saha, 1937), they found that the test for CO_2 was negative and that they could not give final identification to the Na_2 hypothesis. They also mentioned the third possibility that unknown lines may be produced by interstellar dust.

In 1938, C. S. Beals and G. H. Blanchet published an article, in which they concentrated on another line which Merrill previously thought to be a vague feature of interstellar origin. Using observations of dozens of O and B stars, they found this line to be located at 4430 Å and although they found it to have lower intensity, the feature was very wide and conspicuous, making it difficult for them to give 4430 Å any certain identification. It was possible to dismiss electronic bands of diatomic molecules as an origin of the band due to the fact that this DIB has a symmetric profile while from diatomic molecules, we would expect it to be asymmetric. However, they could not find any evidence for excluding vibration bands of diatomic molecules, electronic and vibration bands of polyatomic molecules or interstellar dust from being carriers of the band.

At this point, more astronomers started to realize that these unknown features require research. One of the first theorized identifications was the molecule H_2 in a metastable state trapped by dust grains (G. H. Herbig, 1963). Calculations showed that three lines were centred around 4412 Å. However, only photoionization would be able to produce molecules in such states and the absorption feature 4430 Å could only be seen only in the regions with very bright stars. The theory was dismissed due to the fact that conditions in the interstellar medium do not allow high abundance of metastable H_2, even when considering the presence of the grains.

In the late 1960s, dust grains became a popular candidate for the carrier of the diffuse interstellar bands. The problem, however, was that there is no polarization in the observed diffuse interstellar bands. Since the discovery of the grains is associated with polarization, these results showed that the possibility of the grains being the carrier is low. From the theory about dust grains, only unaligned and possibly small grains could be the carriers. This brought the researchers to the notion that considering mostly polyatomic molecules and ions as the source of the bands is most likely to lead to the positive results of the search for the carriers.

2.2 The Search for the Carriers

Searching for the source of the DIBs is a very difficult task. It requires one to come up with a theory of a stable form of some molecule with abundance high enough to account for at least some of the bands. Moreover, laboratory experiments must confirm the position and shape of the lines. It is very difficult to dismiss or confirm many theories because of the high uncertainty of the results from laboratory experiments. The limited precision of the instruments is another thing to consider, especially, when observing the shape of the lines.

As mentioned before, diffuse interstellar bands were discovered when observing the light from stars, which passes through the diffuse interstellar medium. A very important discovery could be to find their presence when the light crosses another type of medium. One of these objects could be, for example, a comet. There are actually three reported observations. Comets 17P (Holmes) and C/2007 W1 (Boattini) were observed only few years ago and O'Malia et al. (2010) tried to find signs of diffuse interstellar bands in them. The attempt was, however, unsuccessful because the nuclei of the comets were not close enough to the lines of sight of the observed stars. Another comet, P/Halley was observed in 1985 with results reported later by Herbig (1990). The observations once again did not show any increase in the intensity of DIBs caused by the comet. It was to be expected,

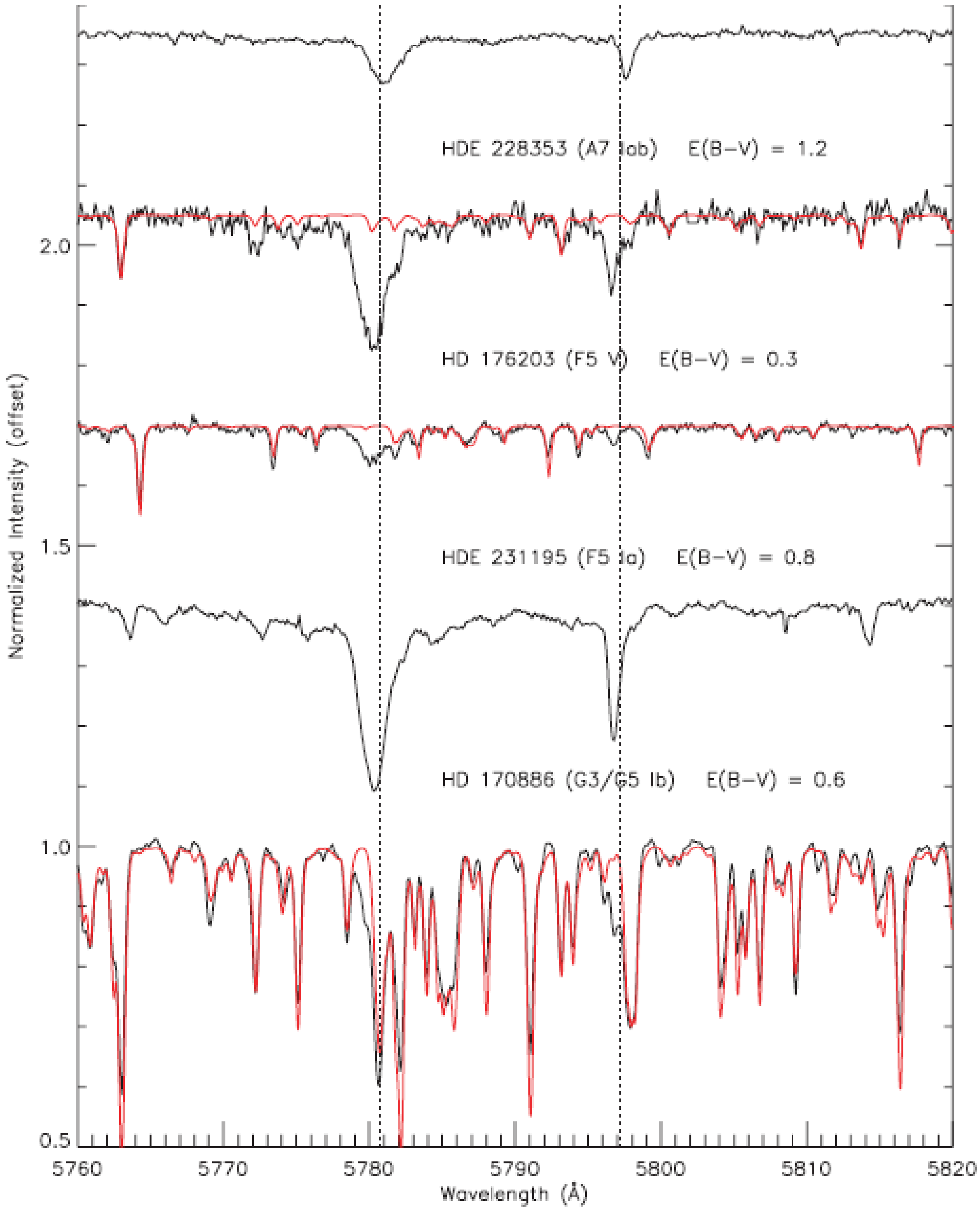


Figure 2.1: Image of spectra of several stars with different colour excess $E(B-V)$. Dotted lines point to the rest wavelength of 5780 Å and 5797 Å bands. Taken from Destree and Snow (2007).

since the composition of the comae are supposed to be different from interstellar. Herbig was unable to find DIBs related to the comet, but he suggested that the relation could not be completely ruled out due to the fact that the carriers could have been destroyed by solar radiation. In another attempt he confirmed the results of the first observation (G. H. Herbig and D. McNally, 1999).

The greatest obstacle in finding the carriers is the lack of information about them. A possible way of finding more about them could be to compare the strength of the DIBs in different lines of sight. Of course, the most informing would be to find carriers themselves. There is a method which could point towards the right molecules or at least, narrow the search. If we order the wavelength/frequency of the diffuse interstellar bands and plot them against their integer values, we get something that looks like a set of energy transitions of a molecule. Using a program to calculate the transition energies corresponding to the same part of the spectrum as DIBs, it should lead us (eventually) to the carriers. Although there are many bands which could originate from different molecules, it is not unwise to assume that many of them have a common carrier. Even if we assume a shift in wavelengths due to the uncertainty of calculation, we may still find the same appearance in the plot as in the case of DIBs, pointing towards the searched molecule.

2.3 Theories

Over the last century, many theories about the possible carriers of the diffuse interstellar bands were discussed. Usually, the greatest obstacle which stands between the theory and the assignment of a line to a carrier is the uncertainty of experiments. To understand the problem of assigning the DIBs, we should take a closer look at some theories. From them, we will be able to see some problems which are part of the research. Although not many lines were correctly associated with atoms and molecules in the interstellar medium, each article may be important, since it may hold additional information about the mysterious bands. There are several interesting hypothetical carriers which were mentioned and researched in articles over the last 20 years.

2.3.1 Ion C_7^-

Because of the advancement of laboratory spectroscopy, research about carbon chain ion C_7^- was made in the 1990s. From the experiments (B. J. McCall et al., 2000), it was shown that three lines were in a strong agreement with 6065 Å, 4964 Å and 6270 Å diffuse interstellar bands. The article mentions two electronic transition systems found in the laboratory spectra, however, one of them would be difficult to observe due to the relatively large width of its lines. The other system was consisting of vibrational spectral bands with the strongest band being at 6270.2 Å, but the rotational structure of the bands was not present due to the low resolution.

The observation of stellar spectra was made using Astrophysical Research Consortium Echelle Spectrometer at Apache Point Observatory. Since it was already known that strength of the DIBs is well correlated with the colour excess $E(B-V)$. Stars with higher colour excess (> 0.85) were picked as well as a couple of unreddened stars, but every one of them was a B-type star. When comparing the laboratory data with observations, the research team found that three interstellar lines very well matched lines found in the experiments, but other two lines were shifted by +7 Å and +10 Å. Nevertheless, the team found it very likely that C_7^- is a carrier of mentioned diffuse interstellar bands.

A couple of years later, B. J. McCall, J. Thorburn, L. M. Hobbs et al. (2001) revisited this hypothesis with data of higher quality. They found that their strongest lines did not actually match the 6270 Å DIB. The centre of the band was shifted approximately 0.6 Å towards red and the shape of the band was also found to be different. Considering chemical models of

Ruffle et al. (1999), which showed that abundance of C_7^- ion could not be high enough to be the carrier due to the destruction of the ions by collisions with atomic hydrogen, the hypothesis was rejected. This research, however, provided very useful information. It is obvious that to be completely certain about the assignment, it is necessary not only to find match in the wavelength, but also in the structure of the line. We can also see how very important, if not crucial, it is to keep on developing more advanced technologies and instruments with the goal to achieve very high resolutions of the spectra.

2.3.2 5069 Å line and Diacetylene

J. Krełowski et al. (2010) published an article which showed evidence of molecule being the carrier of a DIB. Diacetylene ion HC_4H^+ was under laboratory conditions found to possess an absorption feature which coincides with 5069 Å DIB. The position, the shape as well as the width of both features were similar. Authors also mentioned the difference between the laboratory and interstellar conditions when, in space, the temperature and turbulences may change the profile of the line - this is an important fact to consider in every research. Stellar spectra were observed towards OB stars with colour excess $E(B-V)$ value over 0.50. In relation to the theory, it was expected to find relatively high abundance of this molecule in the interstellar medium but no clear conclusions were made, since again, more precise laboratory measurements and high resolution spectra were required.

With better laboratory results, J. P. Maier et al. (2011) showed that at low temperatures, the rotational profile of the band did not match the position of the centre of the 5069 Å line. Also, the shape was different and the authors argumented in the article that HC_4H^+ is most likely not a carrier of 5069 Å feature. The laboratory data introduced interstellar velocity dispersion which changed the results of the previous work and demonstrated how events in the space environment may change the results of observation.

2.3.3 Polycyclic Aromatic Hydrocarbons

PAHs are very popular candidates for carriers of many interstellar bands. Really interesting publication is introduced by D. L. Kokkin et al.(2008) who presented a possibility of $C_{42}H_{18}$, a complicated molecule, being present in the interstellar medium. The strongest feature found in laboratory spectra did not coincide with any diffuse interstellar band but the team suggested that the same technique they used could have been used to find spectra of even more complex molecules. The very problem of this approach is that the more complex and larger the molecule is, the less likely it is to be created in the interstellar environment. When it comes to such molecules, it is necessary to come up with ways how such molecules could become significantly abundant to be responsible for the presence of the DIBs in spectra.

2.3.4 Cyanomethyl Hypothesis

Diffuse interstellar absorption feature at 8037 Å was found to be possibly caused by CH_2CN^- ion (M. A. Cordiner and P. J. Sarre, 2007). It was speculated that due to the nuclear spin statistics of orthto CH_2CN^-, other features would appear in the spectra but were not found. To be a carrier, authors of this work predicted that there must be a mechanism which converts this ion from the ortho to the para form. Another possibility mentioned was that the chemistry by which CH_2CN^- is formed would populate one of the levels in such a way that it would approach Boltzmann distribution at the temperature approximately of 3 K. Transitions were calculated for level populations at 2.74 K showing feature that matches 8037 Å DIB except of the fine structure of the profile.

To this point, only a few articles concerning CH_2CN^- were published. In more recent article (L. Majumdar, A. Das and S. K. Chakrabarti, 2014), calculations support the possibility of given molecule being present in the interstellar medium. For any conclusion, more research is required. However, this specific research shows how much information can be found from quantum mechanical calculations using available computing power we have today. In future, computing transitions of the molecule may become just as important as laboratory and observational data.

Chapter 3

Chosen Interstellar Bands

The main objective of this work was to find new information about DIBs. This may, however, prove to be very difficult if one tries to examine each of the bands. In order to be able to interpret the results of data correlation, it is crucial to understand the relations between the bands as well as to know many of their properties. For this reason, I have chosen only several of the bands and my choice was based on the amount of available information and the strength of the DIBs.

3.1 Properties

Before comparing the bands themselves, it would be appropriate to describe the profiles and properties of 4430 Å, 5780 Å, 5797 Å and 6284 Å bands which are among the strongest DIBs observed in the visible part of the spectrum.

3.1.1 4430 Å

This band differs from others mentioned and even from many more other weaker ones. It is because of the fact that this line is very broad - it is up to a couple of tens of angstroms wide. Although the shape of this band appears to be very symmetric, there is a small difference (E. J. Wampler, 1966) between the wings of the line, as the gradient of rising intensity towards blue is possibly larger than towards red. Snow et al. (1977) found that the linear relation between the strength of the DIB and colour excess $E(B-V)$ has both parameters different from zero. Supported by results from S. Isobe, G. Sasaki, Y. Norimoto (1986), this leads to the assumption that there might be regions from which the absorption band rises without reddening of the star being present. This second team also correlated colour excess with the absorption from two area groups and came to the conclusion that the clouds with lower masses and high velocities could be more important sources of the bands than more massive ones.

In the 1970s, there have been measurements of the polarization of the diffuse interstellar bands with an attempt to test the hypothesis about grains being the carriers. The band at 4430 Å is associated with strong polarization towards the stars HD 183143. P. G. Martin and J. R. P. Angel (1974 and 1975) were searching for polarization variations and blue wing emission associated with the dust but they revealed nothing.

When going through many sets of observed data, one can notice that the interstellar band 4430 Å is missing from many lines of sight while other bands, which will be discussed, are present. Despite its strength, this DIB does not seem to be as common as others are, and when correlating data, it could be important to consider this fact.

3.1.2 5780 Å and 5797 Å

It seems that there is a very good correlation between 5780 Å and 5797 Å DIBs. They both have a complex structure of the profile, especially their wings, and they appear in spectra almost always together. Many observations, however, implicate that these two bands have different carrier. One of the confirmations for this theory was done by Wallerstein and Cardelli (1987). They observed regions of star formation, where researchers expected weaker presence of the two DIBs. Weakening was, for the most part, greater for 5797 Å than for 5780 Å.

Unlike 4430 Å band, they are not very wide (between 2 and 4 Å) but their strength is in their depth. Wesełak et al. (2010) looked into an idea of Doppler splitting of the atomic lines and diffuse bands. This was impossible to do for a long time, as DIBs are much wider than atomic lines which are associated with the discovery of Doppler splitting (first demonstrated by Herbig and Soderblom in 1982). Wesełak's team found splitting in many bands among which 5780 Å and 5797 Å are included as well.

As we have already discussed, DIBs are usually observed in the lines of sight towards hot stars of spectral type O and B. However, there have been many observations towards cool stars. These observations provide less accurate data but definitely show the presence of 5780 Å and 5797 Å diffuse interstellar bands (for example Destree and Snow, 2007). This leads to a suggestion that with more powerful observational instruments, we may get spectra of both hot and cool stars and increase the number of data used for correlations. Another important information which can be found is that these two DIBs are very slightly polarized. Again, they most likely do not originate from the grains (for example results from Cox et al., 2007) but rather from the clouds of large molecules.

A fascinating article was released by the team Cordiner et al. (2008) which reported observations of two distant objects – Andromeda (M 31) and Triangulum (M 33) galaxies. In both cases, 5780 Å and 5797 Å were found to be present in the interstellar medium of the galaxies. The team found that the correlations between the strengths of observed DIBs are almost the same as in the Galaxy. If this is true for other galaxies (which are preferably not part of Local Group), it would point to the fact that every included galaxy evolves in almost the same way (excluding external interference). This assumption could also mean that the interstellar medium does not evolve along with the stars and to prove this, correlation between metallicities of the stars of different populations and strengths of the bands is required.

3.1.3 6284 Å

With high S/N ratio observations, one can observe the details of this band and find that its shape is very specific. There are two apparent lines or bands (not necessarily interstellar) which blend into the 6284 Å DIB's wings. The surrounding of this band is affected by atmospheric molecular oxygen absorption lines (O_2, H_2O) which may contaminate the spectrum observed around this DIB if they are not removed. When compared with other discussed DIBs, it is not as wide as 4430 Å, making it easier to find it in spectra, and it is also not as sharp as 5780 Å and 5797 Å lines. Therefore, it is connected with conclusion that that this line is perfect for observation - very strong and neither wide nor narrow. On the other side, its width is a disadvantage because it would not be the best for observations of Doppler splitting (however, they have been made successfully).

NGC 1448 is a spiral galaxy located in the constellation Horologium. The distance between the Galaxy and NGC 1448 is around 15 Mpc (Tully et al., 2008) and it is another example of galaxy where diffuse interstellar bands were observed. Sollerman et al. (2005) successfully observed DIBs towards the two supernovae (SN 2001 eI and SN 2003hn) in this object. Bands 6284 Å and 5780 Å are the only ones mentioned to have acceptable S/N ratio in both lines of sight. Although 6284 Å band looks almost like the one observed in our Galaxy, the S/N ratio is too low to be able to find detailed structures of its profile.

Fahlman and Walker (1975) found a differential polarization in the vicinity of 6284 Å interstellar band. Observations were made towards B type pulsating star (HD 183143) but no explanation for their discovery had been made. Just as 5780 Å and 5797 Å, this band is also associated with observations by Cox et al. (2007). This team, on the other hand, found change in polarization to be too low, suggesting that there is perhaps no polarization associated with this band at all.

3.2 Correlations between the Bands

Finding the correlations between different DIBs is very important when searching for the carriers. This is done when we plot the strength of two lines against each other and the result is going to be most likely a linear function. However, this linear function does not have to fit the plotted data very well, therefore, we use a correlation coefficient which tells us how well the strengths are correlated. This coefficient can be calculated by using formula

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{n(\sum x^2) - (\sum x)^2}\sqrt{n(\sum y^2) - (\sum y)^2}}\,. \tag{3.1}$$

Another way how to describe a correlation is by the means of coefficient of determination. The calculation is simple $-$ we just take the square value of correlation coefficient r^2. By doing this, we can describe how much percent of the plotted data can be associated with the fitted linear function which is usually determined by the method of least squares.

3.2.1 Method of Least Squares

This method of fitting plotted data uses very simple principle. Let us assume that we have point in an already fitted graph. When we draw a line downwards (or upwards) towards the fit, we get the distance and the square of this distance removes $\pm$ sign and gives us a notion about how well this point corresponds to the fit. If the square has a value of zero then the point precisely lies on the fitted function. The method itself uses this principle and makes it possible to find the coefficients of function which is supposed to describe the plot.

This does not have to be trivial task. If we, for example, take a look at certain regions of different functions, we will find that they may look almost the same. The best example would be a poor set of data which looks like that it would be best fitted by an exponential function, but in reality, it can be correctly expressed by one (or a combination of many different) harmonic function. This problem can be seen even from a purely mathematical perspective, since we have a relation

$$e^{i\phi} = \cos\phi + i\sin\phi\,. \tag{3.2}$$

Luckily, in the case of comparing strengths of the bands, the relations are mostly linear.

Our goal is to find the coefficients of the function. To do this, we have to pick a function with which we want to fit the data. Here, the relations are linear and therefore, it is important to discuss two specific parameters – one defines the gradient, or slope, of the function and another shifts the fit on the vertical axis. To find a solution of parameters which are to be used to get a best fit, we can use the following equation

$$\chi^2(\beta) = \sum_{i=1}^{n} (y_i - f(x_i\,,\beta))^2\,w_i\,, \tag{3.3}$$

which expresses the sum of all squares produced by the data in the plot. y_i represents the function value of the data, $f(x_i,\beta)$ the function we want to fit and w_i the weight of the given measurement. Since we want this sum to be minimal

$$\nabla\,(\chi^2) = 0\,, \tag{3.4}$$

we have only to solve one set of equations

$$\sum_{i=i}^{n} \boldsymbol{v}_i\,f(x_i,\,\beta)\,w_i = \sum_{i=i}^{n} \boldsymbol{v}_i\,y_i\,w_i\,, \tag{3.5}$$

$$\boldsymbol{v}_i = \mathrm{grad}f(x_i,\,\beta)\,. \tag{3.6}$$

Sometimes, another part of solving this problem is to find the uncertainties σ_i which are related to the weight w_i that is necessary for solving the set of equations. The given problem is not discussed in this work due to the fact that the uncertainties of strength of the DIBs tend to be very large, quite unreliable and sometimes, not even mentioned. I am therefore setting values $w_i = 1$.

3.2.2 Correlations between 5780 Å, 5797 Å, 6284 Å and 4430 Å

To make correlation between two bands, three different sets of data were used, taken from Vizier. The first set was produced by Xiang et al. (2011) but was altered by us for the purpose of the final chapter – the number of data is therefore reduced. The second set (Snow et al., 1977) was chosen for the reason of having much richer data. But since most measurements are done mostly between 5000 Å and 7000 Å, values for 4430 Å DIB are missing in both sets. This was the reason for choosing the third set of data by Guarinos et al. (1988). It once again provides strengths of 5780 Å, 5797 Å and 6284 Å but also a very large number of measurments of 4430 Å. Equivalent widths of this band were ploted against other DIBs from the altered data set from Xiang. The plots and the coefficients of the determination obtained using QtiPlot for each chosen diffuse band are provided in this work.

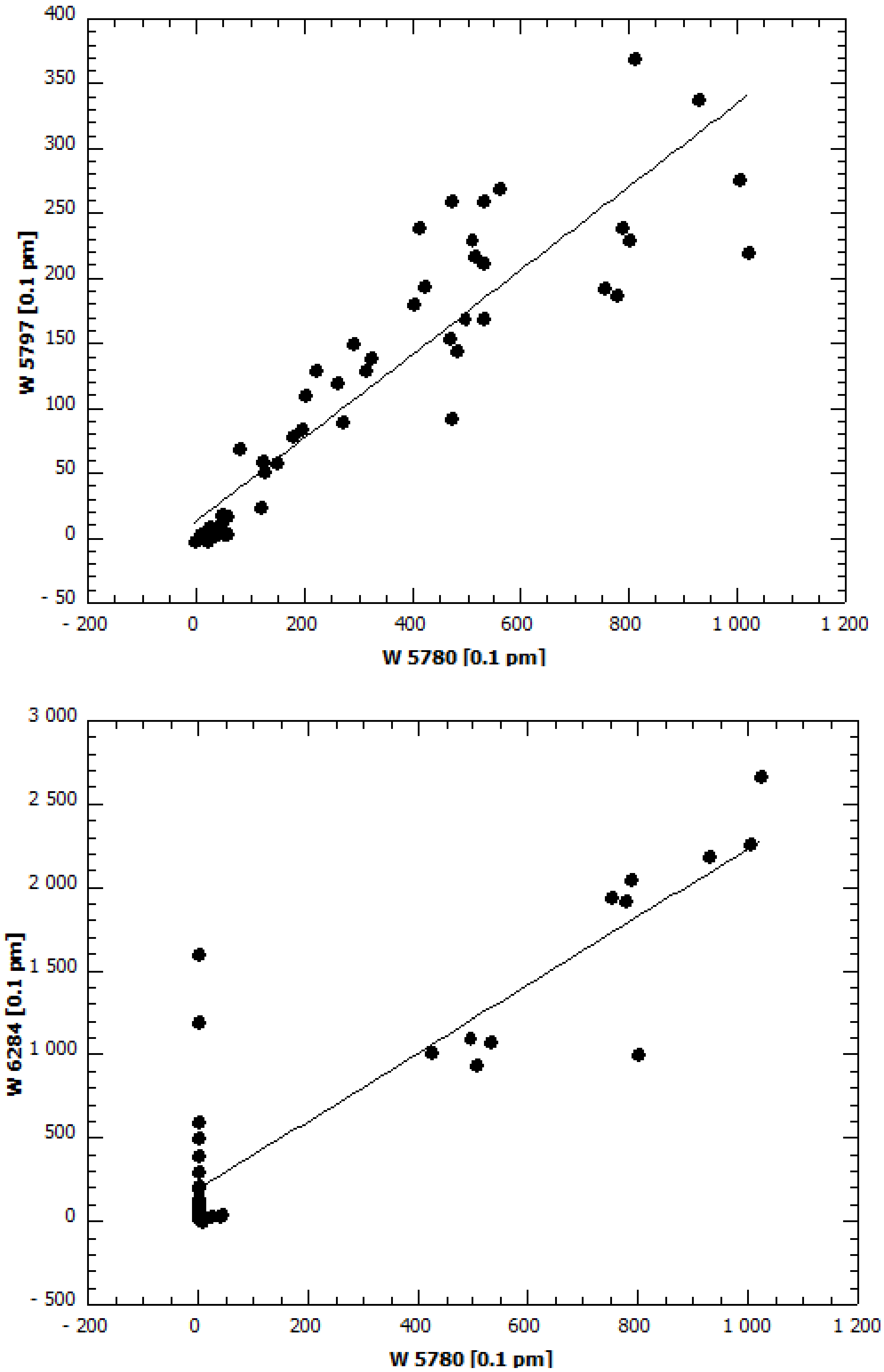


Figure 3.1: Correlation between W5780 and W5797 with coefficient of determination $r^2 = 0.835$ (top) and between W5780 and W6284 with $r^2 = 0.801$ (bottom); Guarinos (1988).

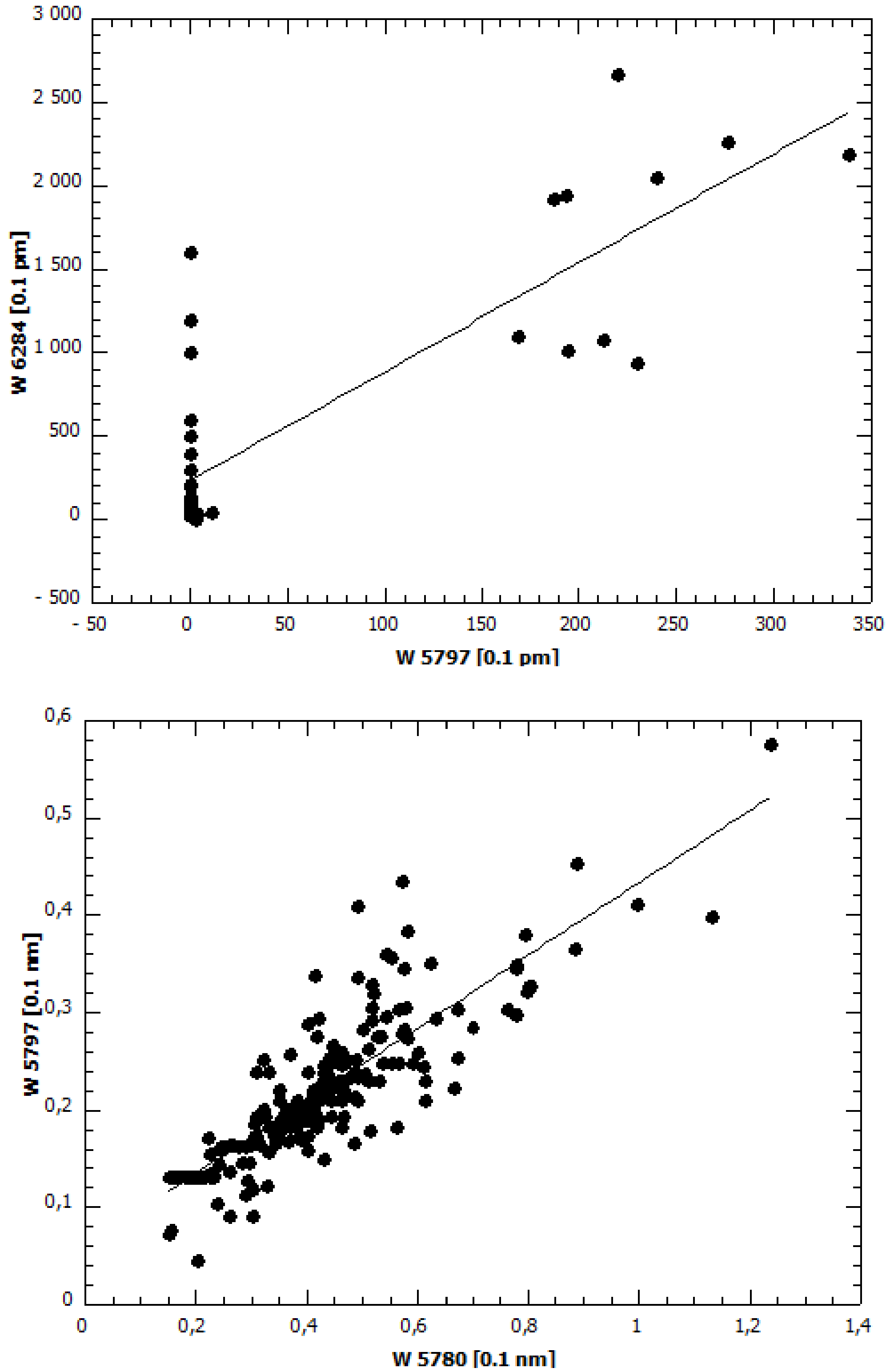
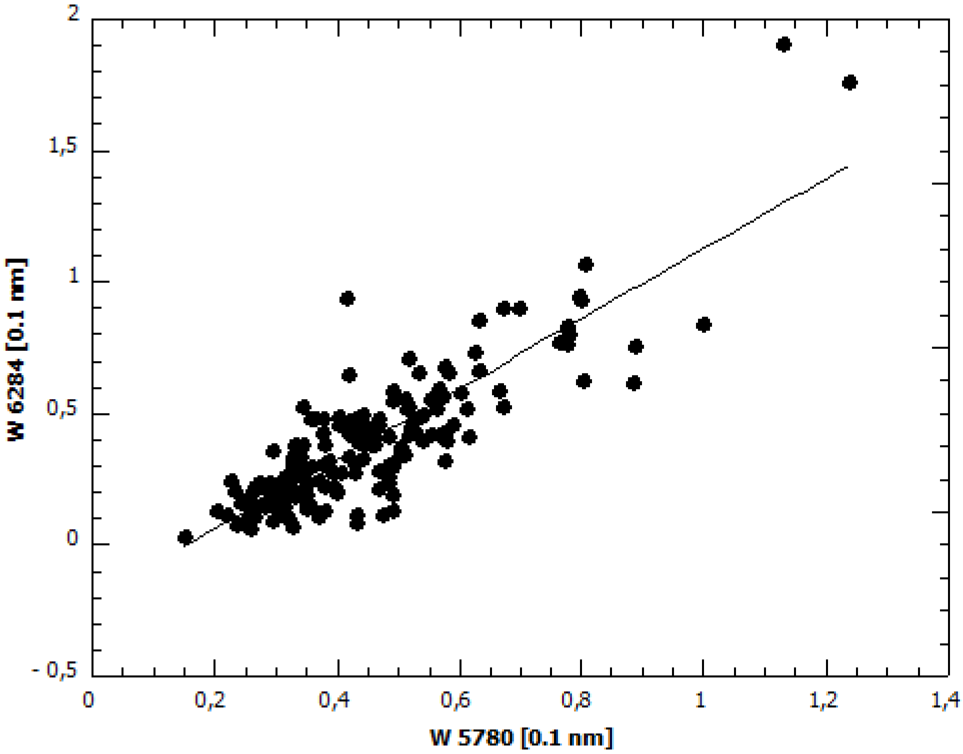


Figure 3.2: Correlation between W5797 and W6284 with coefficient of determination $r^2 = 0.709$ (top); Guarinos (1988). Picture below shows the correlation between W5780 and W5797 with $r^2 = 0.744$; Snow et al. (1977).



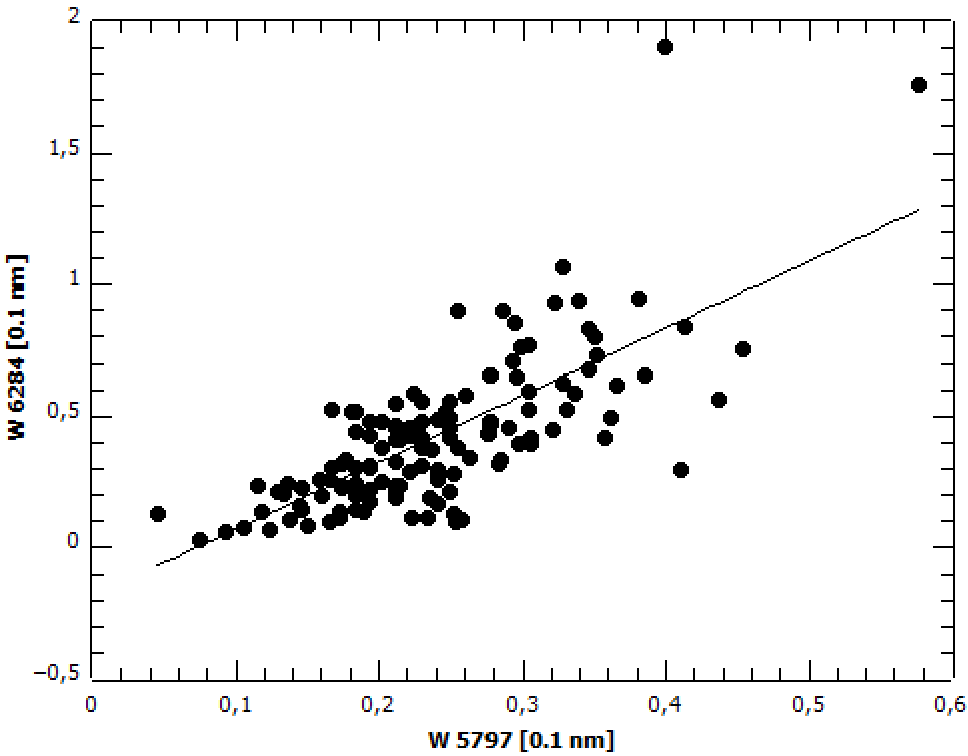


Figure 3.3: Correlation between W5780 and W6284 with coefficient of determination $r^2 = 0.739$ (top) and between W5797 and W6284 with $r^2 = 0.534$ (bottom); Snow et al. (1977).

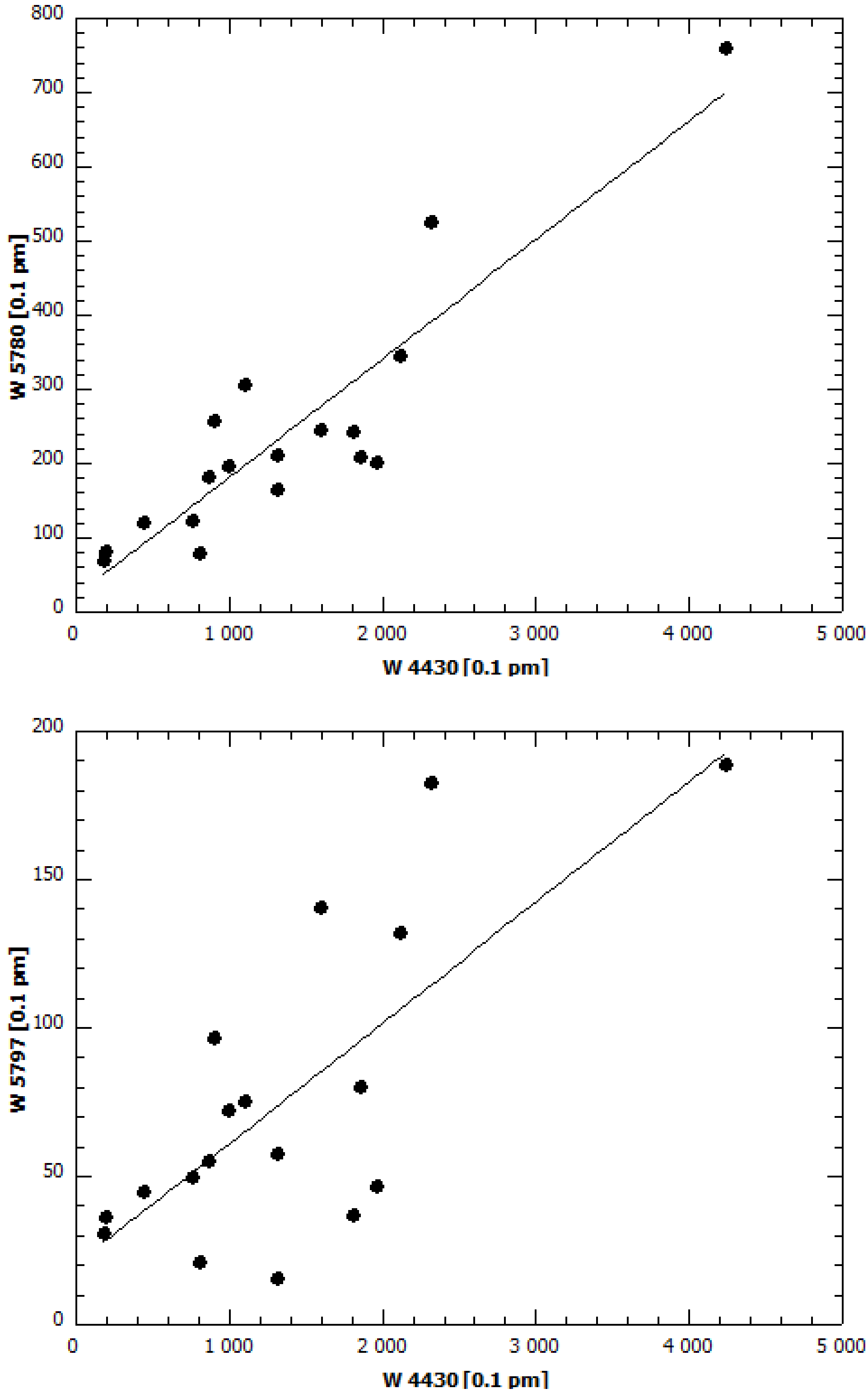


Figure 3.4: Correlations between W4430 and W5780 (top, $r^2 = 0.814$) and W5797 (bottom, $r^2 = 0.547$); combined W4430 from Guarinos (1988) with Xiang et al. (2011).

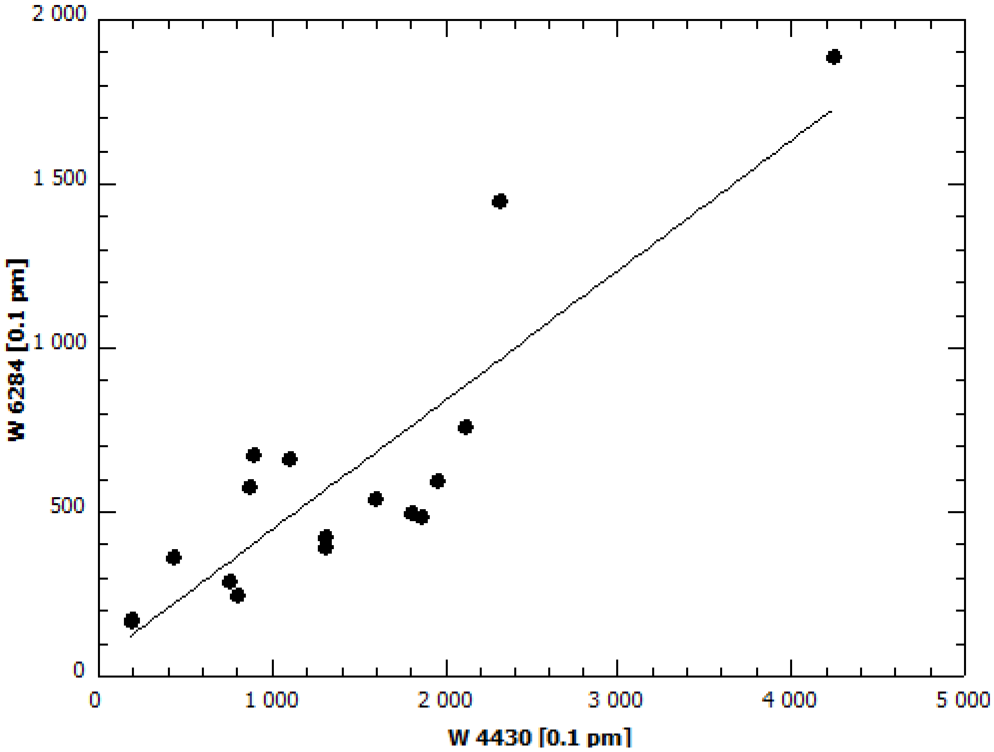


Figure 3.5: Correlation between W4430 and W6284 with coefficient of determination $r^2 = 0.764$; combined W4430 from Guarinos (1988) with Xiang et al. (2011).

We can see that three of four bands are quite well correlated with each other. The only DIB which does not seem to be correlated with others is the 5797 Å band. It may be due to the fact that 5780 Å, 6284 Å and 4430 Å probably have similar source (not necessarily common carrier) while the carrier of 5797 Å differs from others. To make more specific predictions about the carriers from these correlations, new and more accurate data measured at each of mentioned bands from hundreds or even thousands of lines of sight would be required. However, even from these plots we can see that DIBs can be divided into families – they seem to have different carriers.

Chapter 4

Solar Neighbourhood and the DIBs

Since the DIBs originate from the interstellar medium, we have to consider the properties of our Galaxy within which we are searching for the carriers of the bands. Therefore, in our case, the research was focused on the relation between the equivalent width and Galactic coordinates. One of them would be the colour excess which indicates the amount of extinction and therefore, also the amount of material between us (observers) and the observed stars. Most important investigation was finding the relation between strengths of the bands and lines of sight. Cheking the correlation with stellar metallicities [Fe/H] could also provide useful information.

To find x, y, z coordinates of an object, we have to know its galactic longitude l, galactic latitude b and distance r. The relations between the sets of coordinates are

$$r^2 = x^2 + y^2 + z^2 \,, \tag{4.1}$$

$$x = r \cos b \cos l \,, \tag{4.2}$$

$$y = r \cos b \sin l \,, \tag{4.3}$$

$$z = r \sin b \,. \tag{4.4}$$

The problem with (x, y, z) coordinates is that most of research works usually contain only information about the longitude and latitude. Knowledge of the distance of the object is not mentioned in all previously used sets of data. We were able to get information about the stellar distances concerning the first set of data by Xiang. I had to reduce the number of stars and that means that plots where poor on data. Moreover, neither of the three data sets contained information about the metallicity of the observed stars. These reasons led to the search for other works and finally, the needed data were found in the publications introduced by Chen et al. (2013) and Raimond et al. (2012). Chen's data contain information about 6284 Å band, colour excess $E(B-V)$ and metallicity [Fe/H]. Reimond's data were chosen from the reason that he also provided the distances of the stars and made it possible for us to find their (x, y, z) coordinates. The only disadvantage is that it contains only 150 stars, although it is still about four times more than our reduced data from Xiang.

4.1 Expectations

Before presenting the correlations and coming to a discussion, it would be appropriate to mention what we expect to find, based on our present knowledge of our Galaxy, interstellar medium and Solar neighbourhood.

The first step of the investigation was to look into the relations between DIBs and Galactic coordinates x, y, z and l, b, r. Since every galaxy is supposed to be a relatively thin disk, galactic latitude carries almost the same information as the perpendicular distance from the galactic plane (z). The difference is in the fact that the Sun is located slightly above the plane. Since the information is supposed to originate from the interstellar medium, the further we go from the galactic plane, the weaker the DIBs ought to be.

The coordinate x is defined as distance from the Sun with unit vector pointed towards the Galactic centre and y is pointed in the direction of the moving Sun within the Galaxy. Distance between us and the observed stars could be calculated as the square root of the sums of squares of x, y and z coordinates. Galactic longitude is the angle at which the object can be found. Its value is $l = 0$ for Galactic centre and rises in the same direction as the Sun orbits the Galaxy. Predictions could be made for each of these coordinates but it would require us to consider some simplifications which would most likely not match our observations. These four correlations almost solely depend on the distribution of matter in the Solar neighbourhood and therefore, they should be compared with available extinction maps. Once this is done, we should get a picture about the distribution of the carriers within the ISM of our neighbourhood.

I have mentioned in previous chapters that the strength of DIBs is very well correlated with the colour excess. But it has been also seen that the bands are not perfectly correlated with each other. It was therefore necessary to revisit this relation and see what is to be found.

The last correlation we looked at is between the equivalent width of 6284 Å and metallicity [Fe/H]. It is almost impossible to predict this relation but I would expect that the amount of carriers and the strength of the band should somehow depend on the generation of stars because as we have already mentioned, the stars dramatically alter the interstellar medium around them in their final stages of evolution.

4.2 Data from Hipparcos

Data set from Xiang et al. (2011) does not contain information about stellar distances which are needed for finding the x, y, z coordinates, as follows from (4.1). We had to reach for Hipparcos database, where we were able to find radial distances of some stars, for which Xiang provided equivalent widths of three DIBs. The following table contains information about these stars.

HD	$E(B-V)$	r [pc]	x [pc]	y [pc]	z[pc]	l [°]	b [°]
2905	0.433	1369.860	-702.00	1176.00	3.00	120.8361	0.1351
21291	0.604	595.240	-465.00	370.00	30.00	141.4976	2.8782
21483	0.562	534.760	-465.00	180.00	-194.00	158.8727	-21.3030
27778	0.349	278.550	-264.00	33.00	-83.00	172.7629	-17.3928
29647	0.987	124.690	-121.00	13.00	-29.00	174.0529	-13.3487
30614	0.323	1923.080	-1511.00	1095.00	467.00	144.0656	14.0424
34078	0.530	574.710	-569.00	79.00	-23.00	172.0813	-2.2592
37023	0.345	712.92	-588.00	-326.00	-237.00	209.0107	-19.3803
37061	0.525	444.440	-367.00	-203.00	-147.00	208.9248	-19.2736
37903	0.349	297.620	-255.00	-129.00	-85.00	206.8512	-16.5375
41117	0.581	552.490	-545.00	-93.00	-8.00	189.6918	-0.8604
46202	0.470	1317.83	-1181.00	-584.00	-46.00	206.3134	-2.0035
48099	0.254	854.700	-767.00	-377.00	12.00	206.2096	0.7982
142096	0.170	94.880	85.00	-14.00	41.00	350.7244	25.3801
143275	0.157	150.600	137.00	-24.00	58.00	350.0970	22.4905
144217	0.192	123.920	113.00	-13.00	50.00	353.1929	23.5997
144470	0.228	144.510	132.00	-17.00	56.00	352.7498	22.7730
145502	0.272	145.350	133.00	-13.00	56.00	354.6087	22.7002
147165	0.392	213.680	202.00	-31.00	62.00	351.3130	16.9989
147888	0.511	124.840	118.00	-13.00	38.00	353.6470	17.7093
147889	1.087	118.060	112.00	-14.00	35.00	352.8573	17.0436
147933	0.478	110.740	105.00	-12.00	34.00	353.6860	17.6867
149757	0.307	112.230	102.00	11.00	45.00	6.2811	23.5877
185418	0.512	719.420	427.00	579.00	-27.00	53.6025	-2.1709
193322	0.386	595.240	123.00	582.00	29.00	78.0986	2.7807
199579	0.339	908.66	68.00	906.00	-5.00	85.6967	-0.2996
206267	0.502	606.060	-98.00	597.00	40.00	99.2904	3.7383
207198	0.589	917.430	-207.00	887.00	112.00	103.1362	6.9949
210121		471.700	184.00	282.00	-330.00	56.8751	-44.4610
217068		245.700	102.00	21.00	-222.00	11.8813	-64.8814

Table 4.1: Combined data from Xiang and Hipparcos. Red coloured names of stars indicate very large errors of distance values and coordinates determined from them are less reliable.

4.3 DIBs and Galactic Coordinates

4.3.1 Coordinates *(x, y, z)*

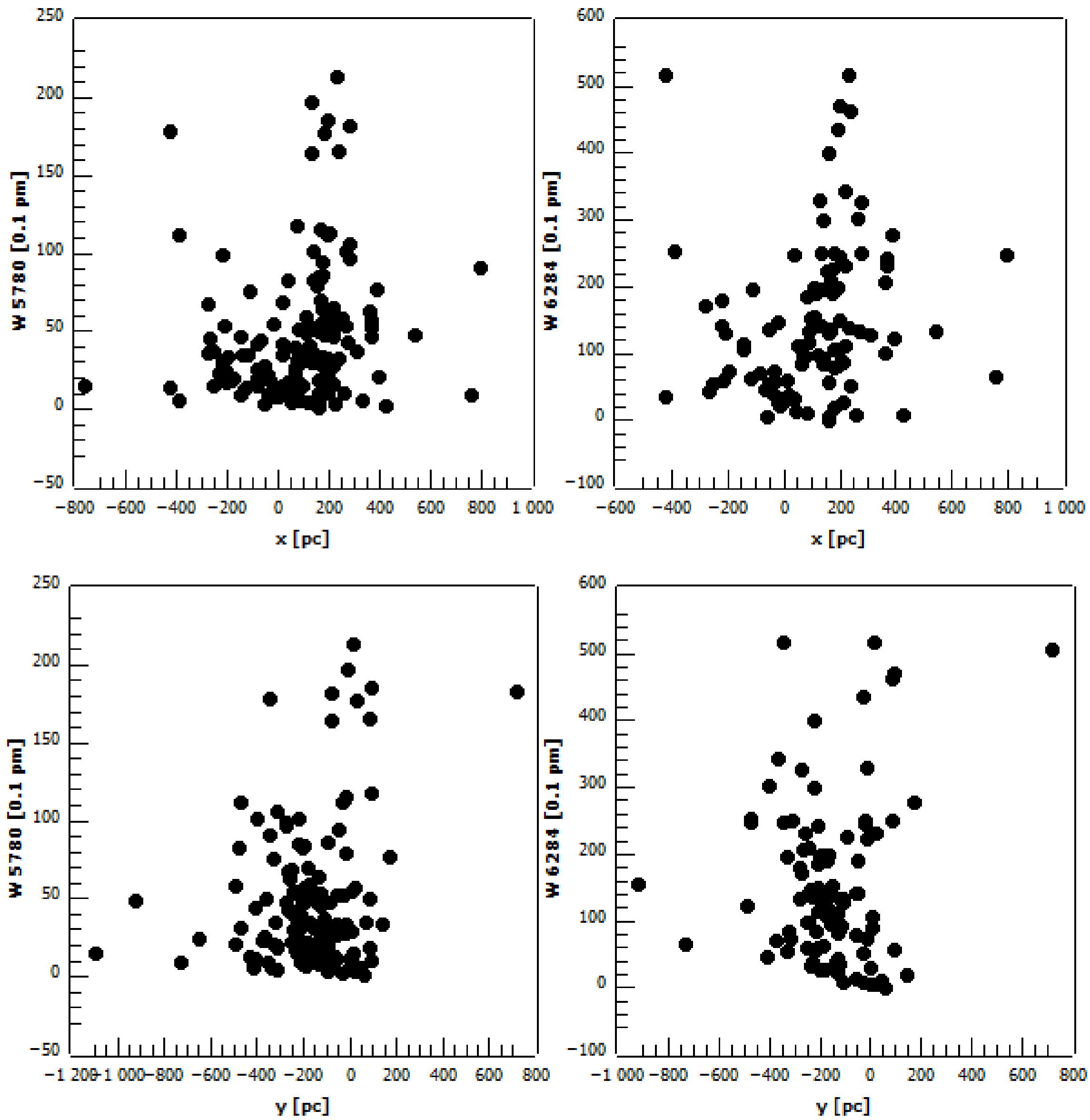


Figure 4.1: Correlations between equivalent widths of two bands and *x* (top) and *y* (bottom) coordinates; Raimond et al. (2012).

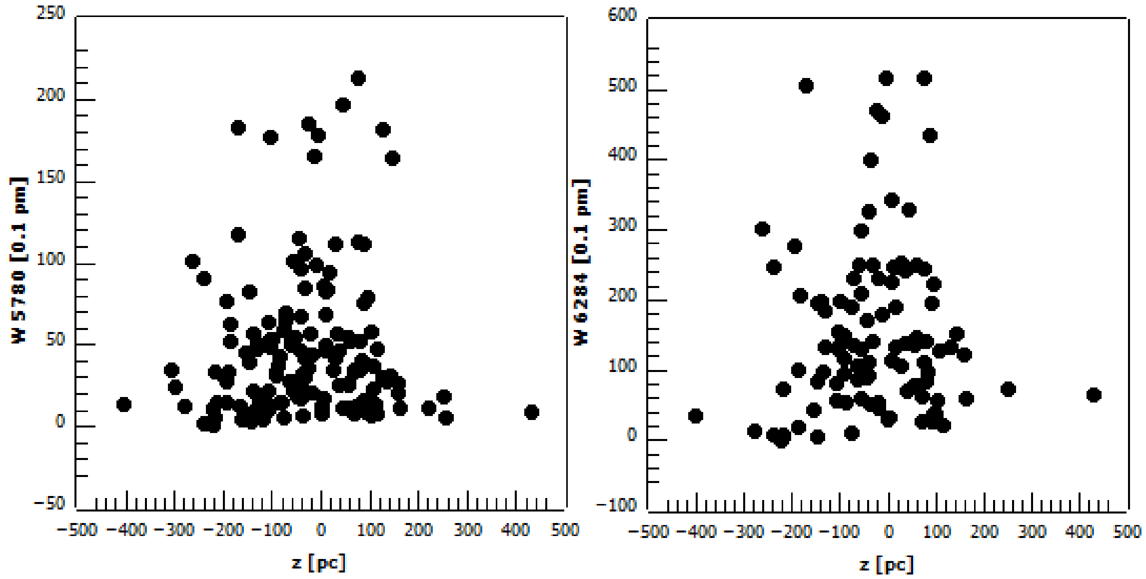


Figure 4.2: Correlations between equivalent widths of two bands and z coordinate; Raimond et al. (2012).

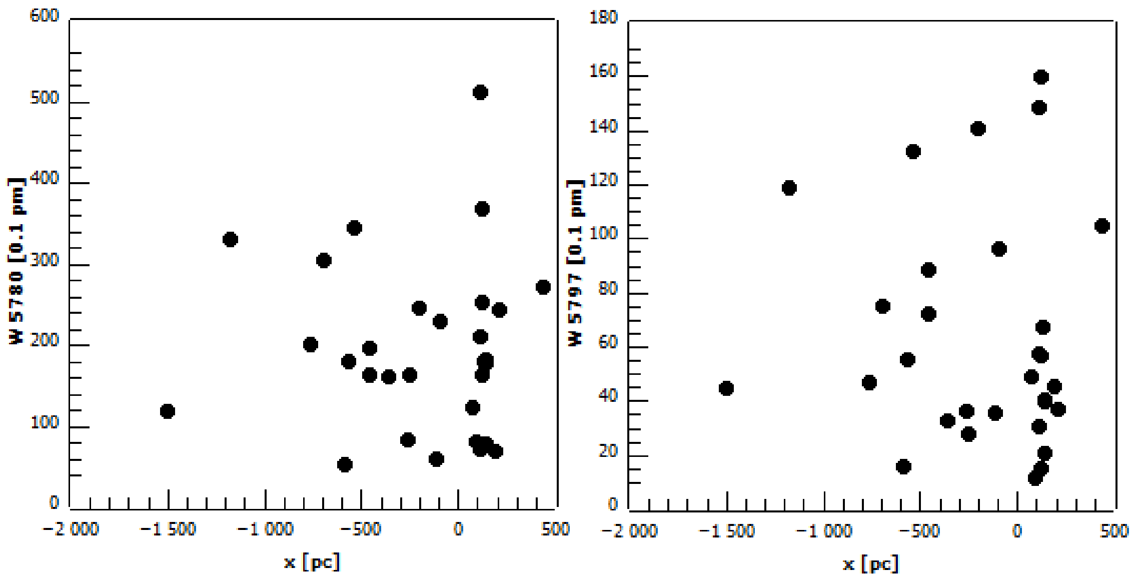


Figure 4.3: Correlations between W5780, W5797 and x coordinate; Xiang et al. (2012). All plots which use data from Xiang were created using Hipparcos database in order to find stellar distances. Coordinates were calculated using relations mentioned at the beginning of this chapter.

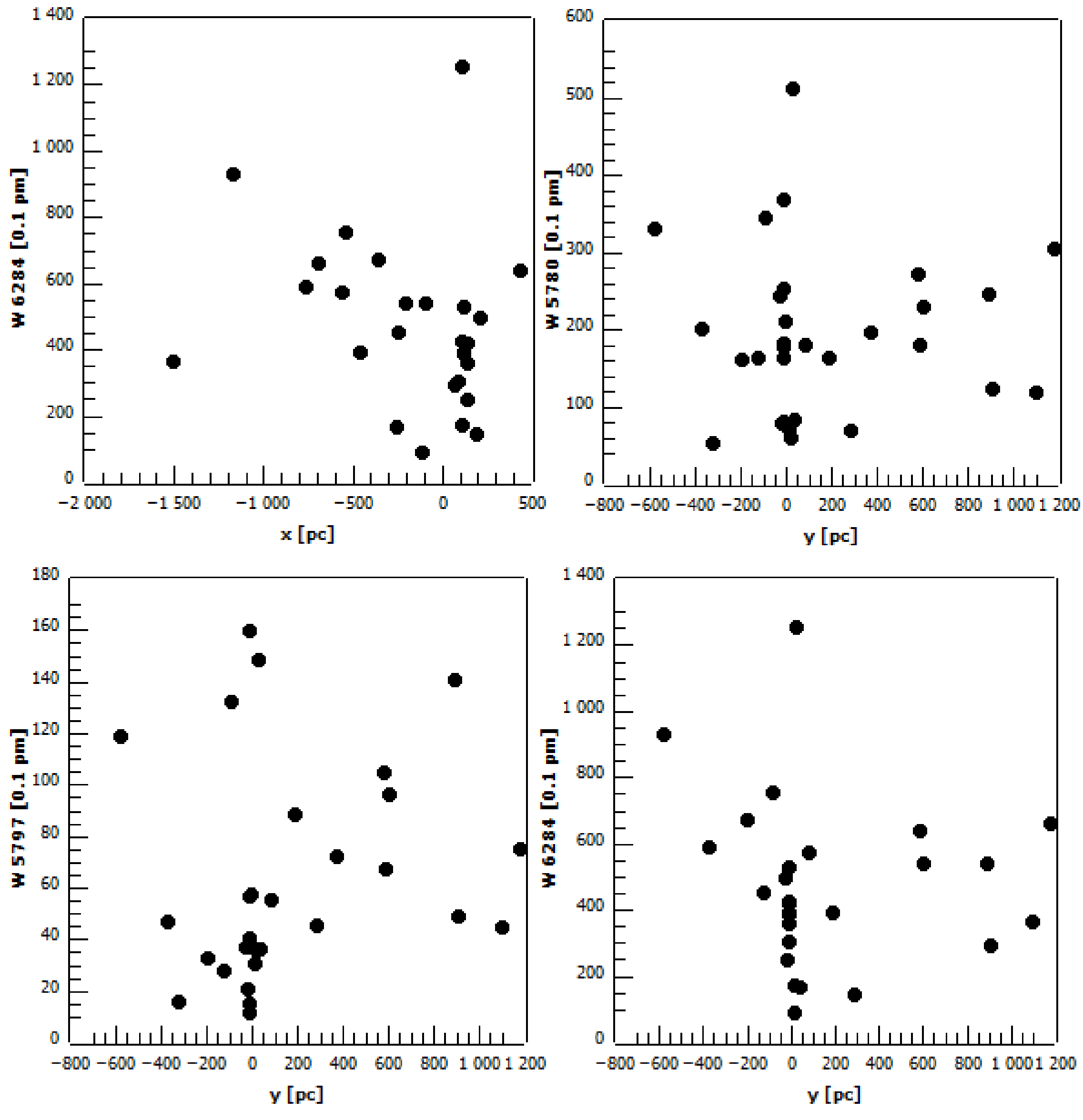


Figure 4.4: Correlations between equivalent widths and x (top left) and y coordinates; Xiang et al. (2012).

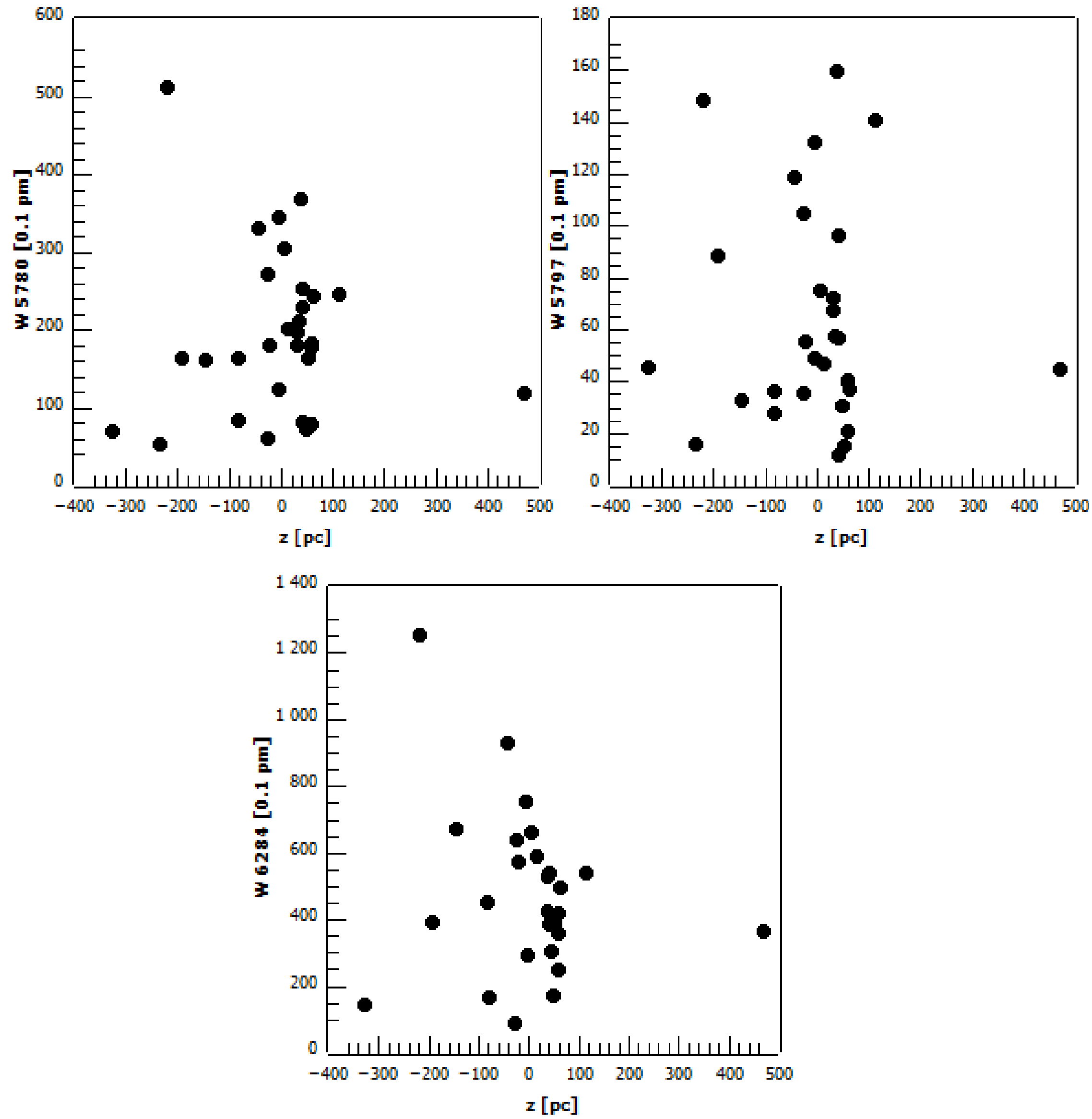


Figure 4.5: Correlations between equivalent widths and z coordinates; Xiang et al. (2012).

4.3.2 Coordinates *(r, l, b)*

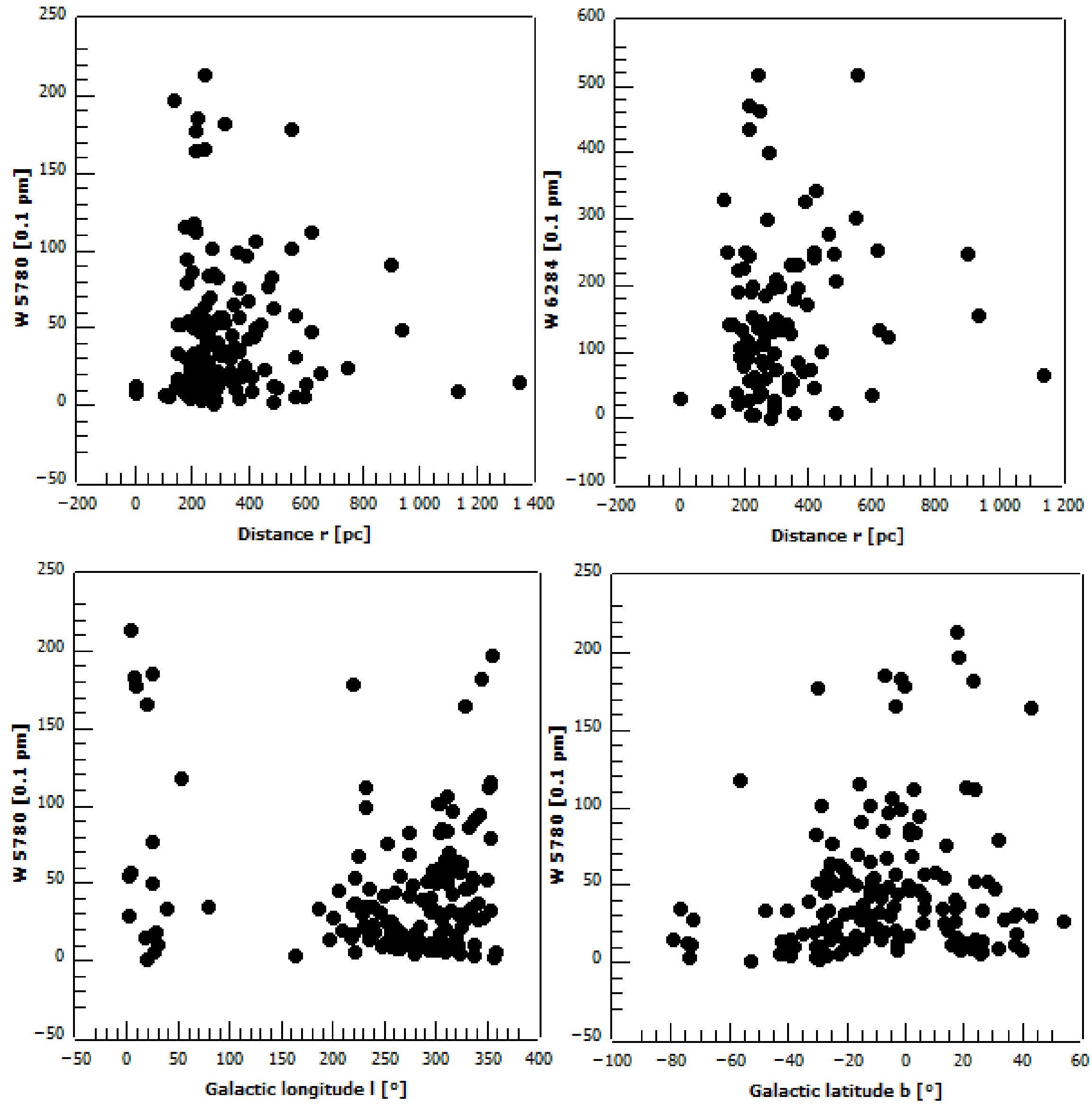


Figure 4.6: Correlations between two equivalent widths, distance *r* (top), Galactic longitude *l* (bottom left) and Galactic latitude *b* (bottom right); Raimond et al. (2012).

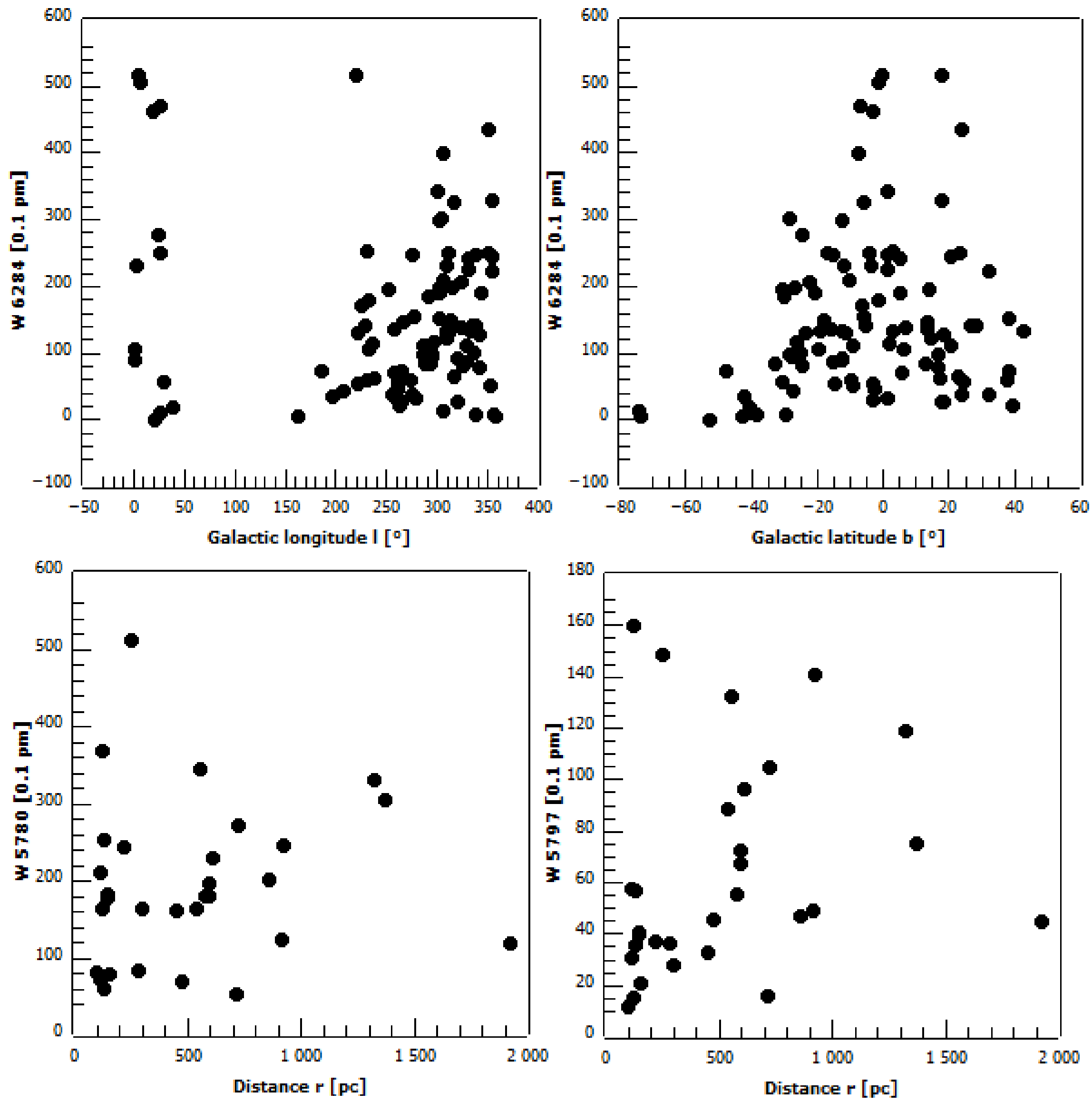


Figure 4.7: Correlations between equivalent widths, Galactic longitude l (top left) and Galactic latitude b (top right); Raimond et al. (2012). Bottom correlations show the relation between equivalent widths and stellar distances r; Xiang et. al (2011).

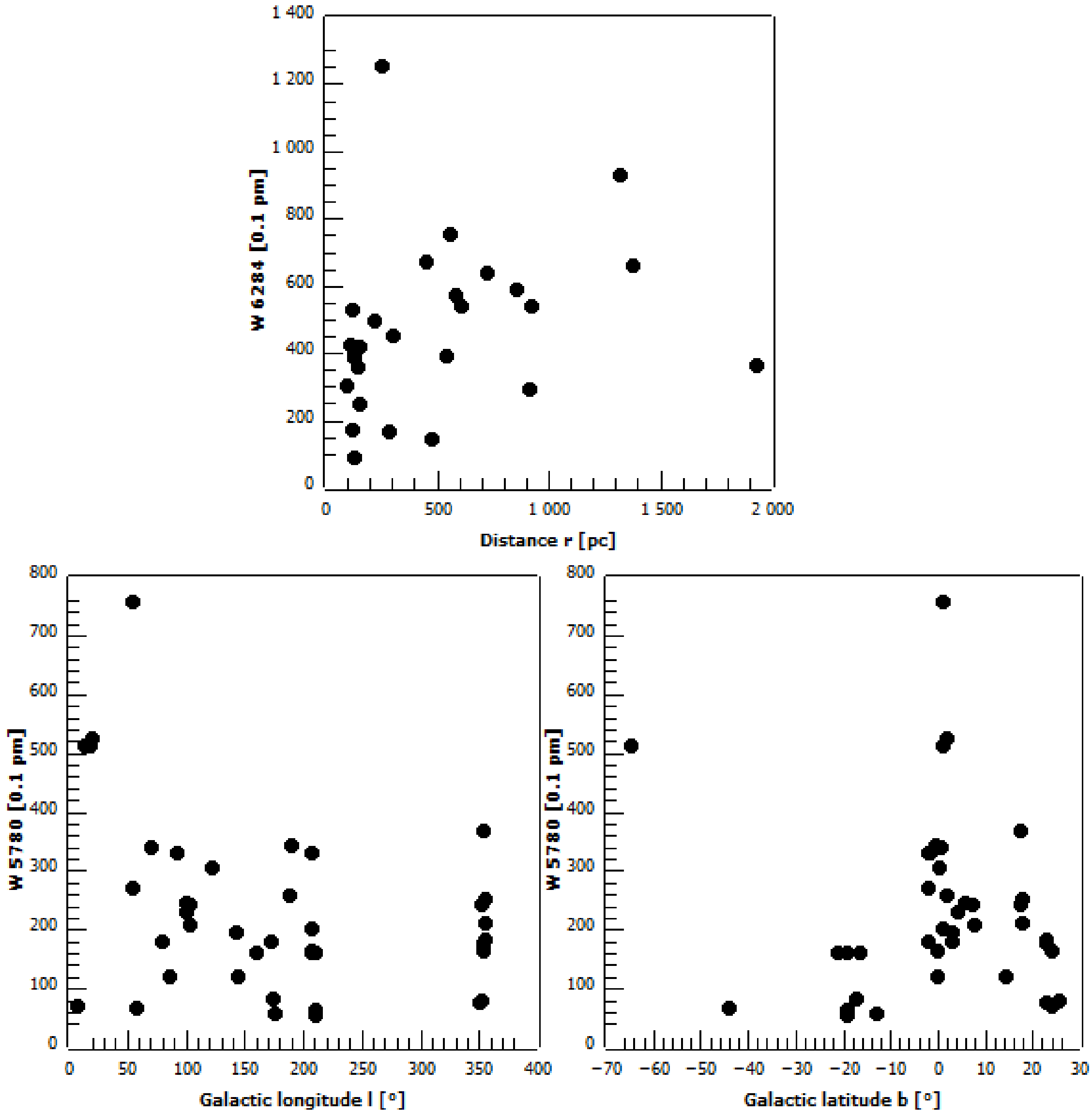


Figure 4.8: Correlations between W6284 and distances r (top) and between W5780, Galactic longitude l (bottom left) and Galactic latitude b (bottom right); Xiang et al. (2011).

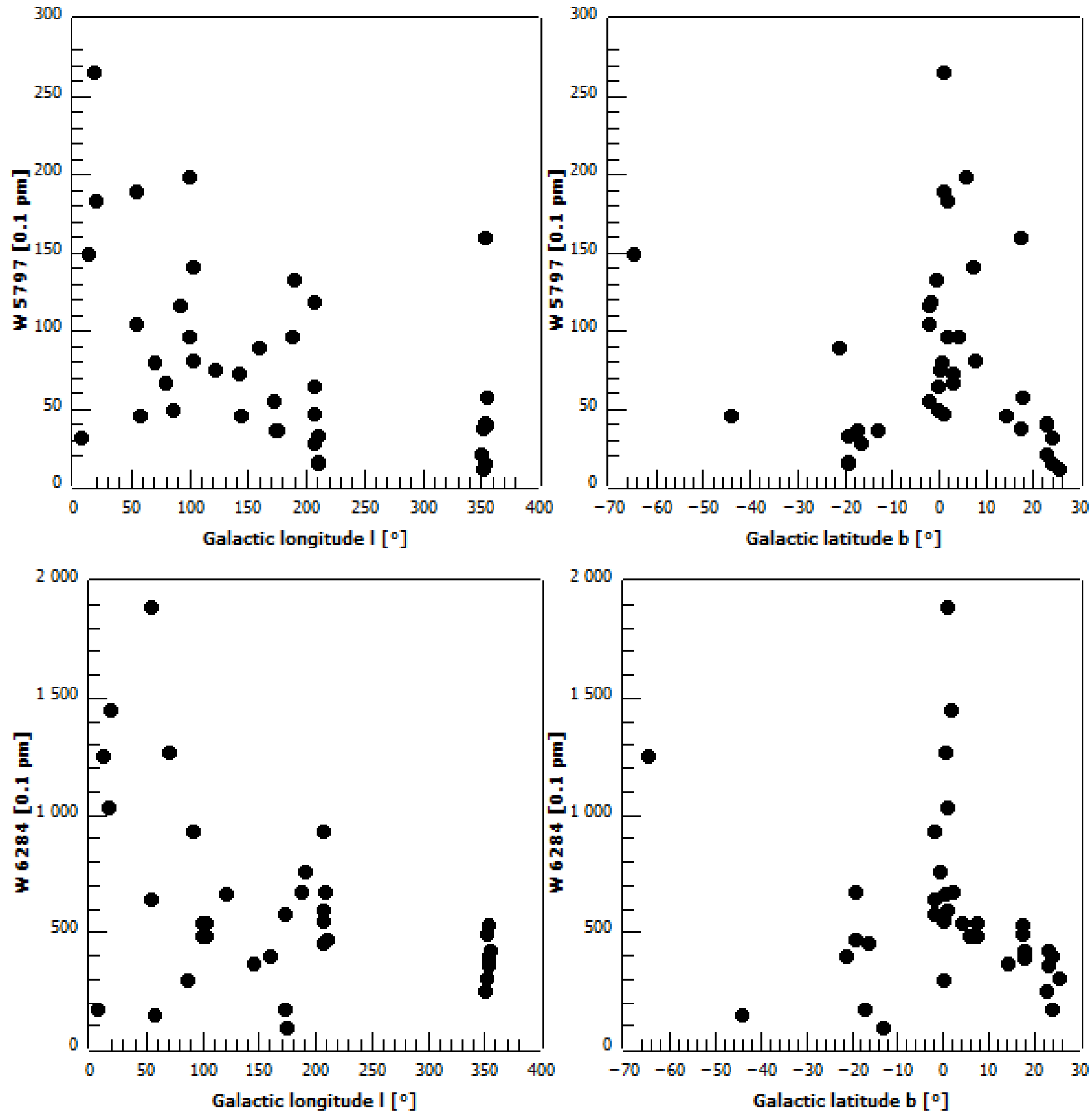


Figure 4.9: Correlations between W5797, Galactic longitude l (top left), Galactic latitude b (top right) and W6284, Galactic longitude l (bottom left) and Galactic latitude b (bottom right); Xiang et al. (2011).

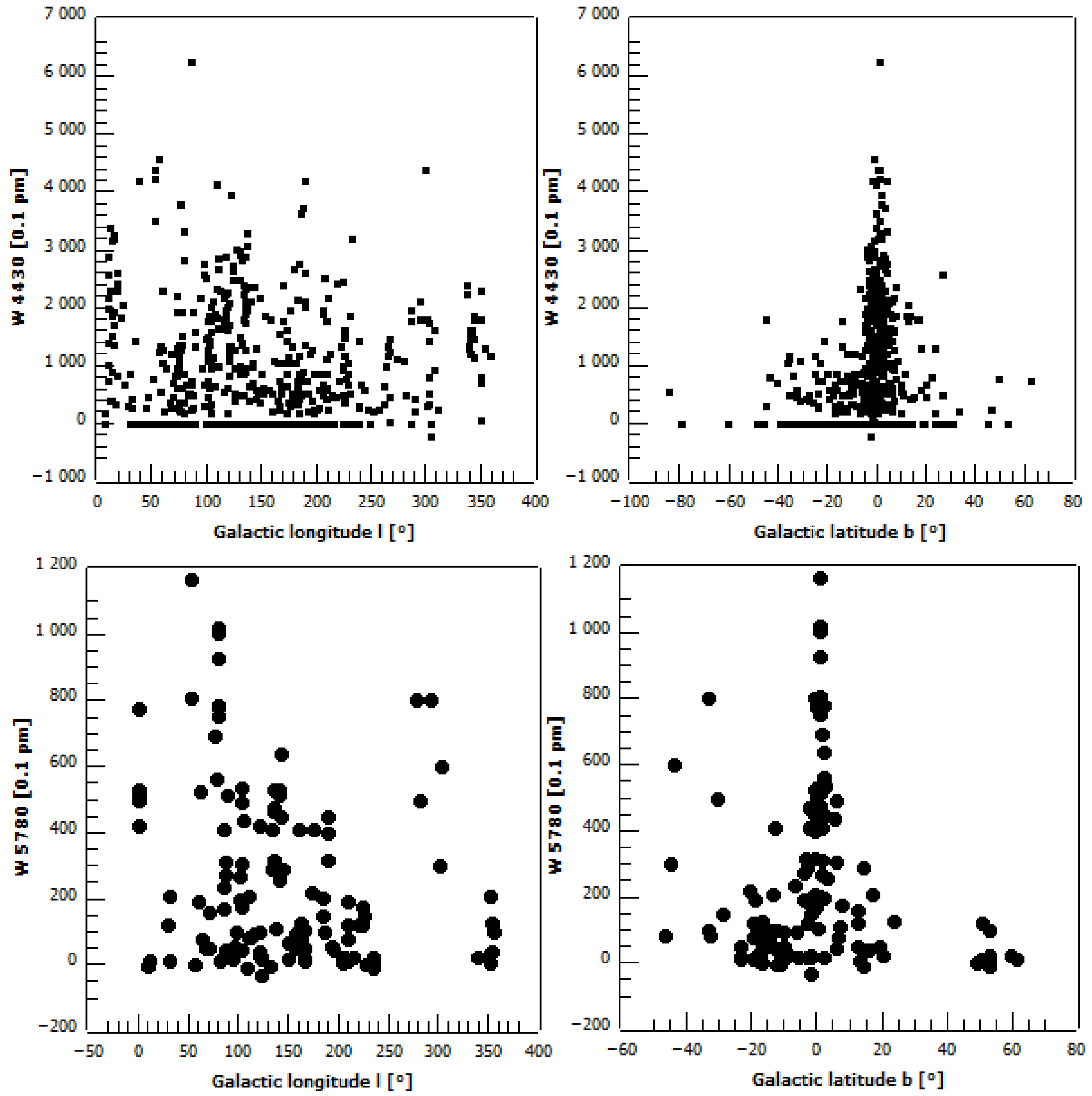


Figure 4.10: Rich plots between W4430, Galactic longitude l (top left) and Galactic latitude b (top right). Bottom correlations were made between W5780, l and b; Guarinos (1988).

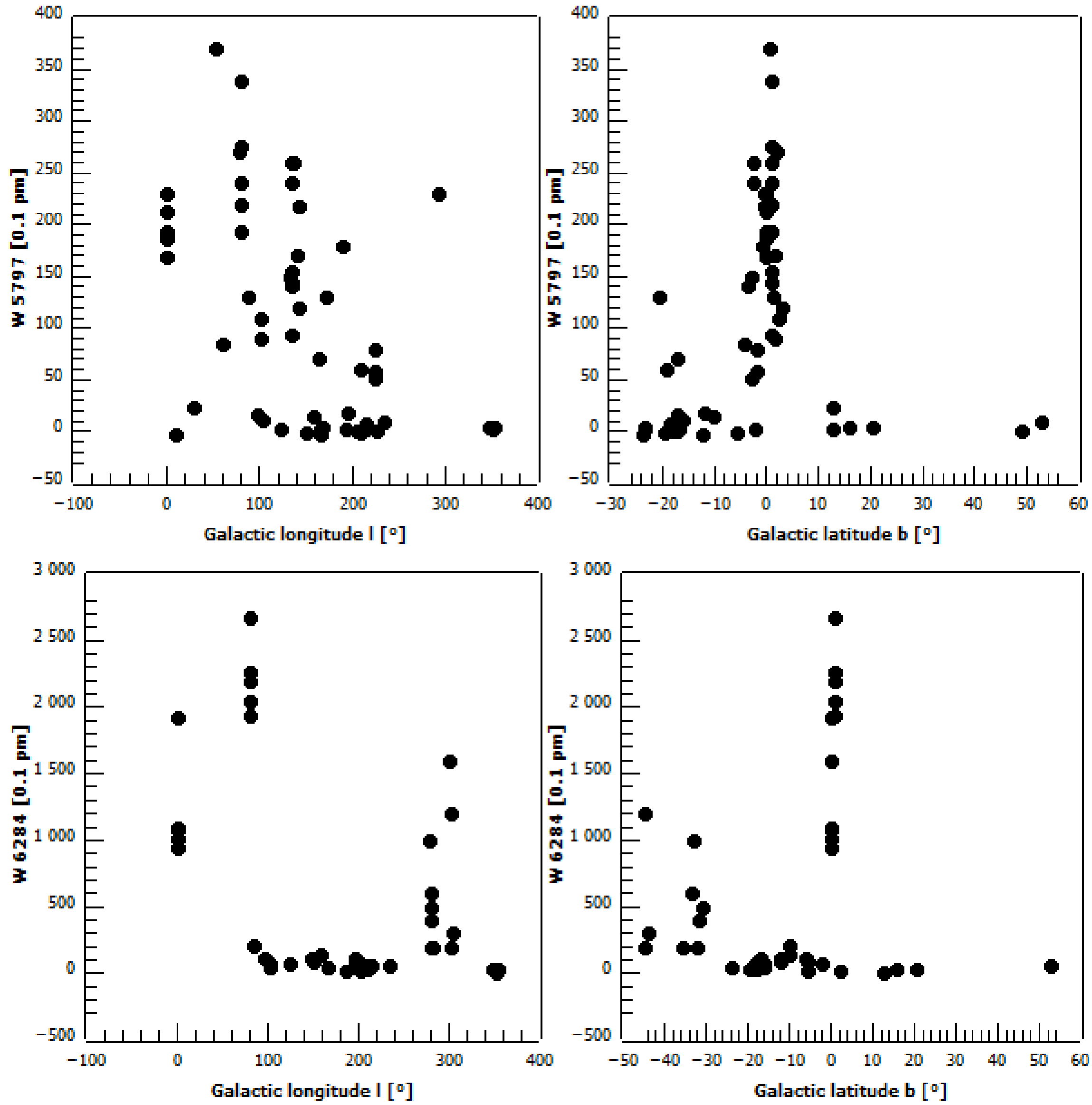


Figure 4.11: Poor correlations between W5797 (top), W6284 (bottom), Galactic longitude l (left) and Galactic latitude b (right); Guarinos (1988).

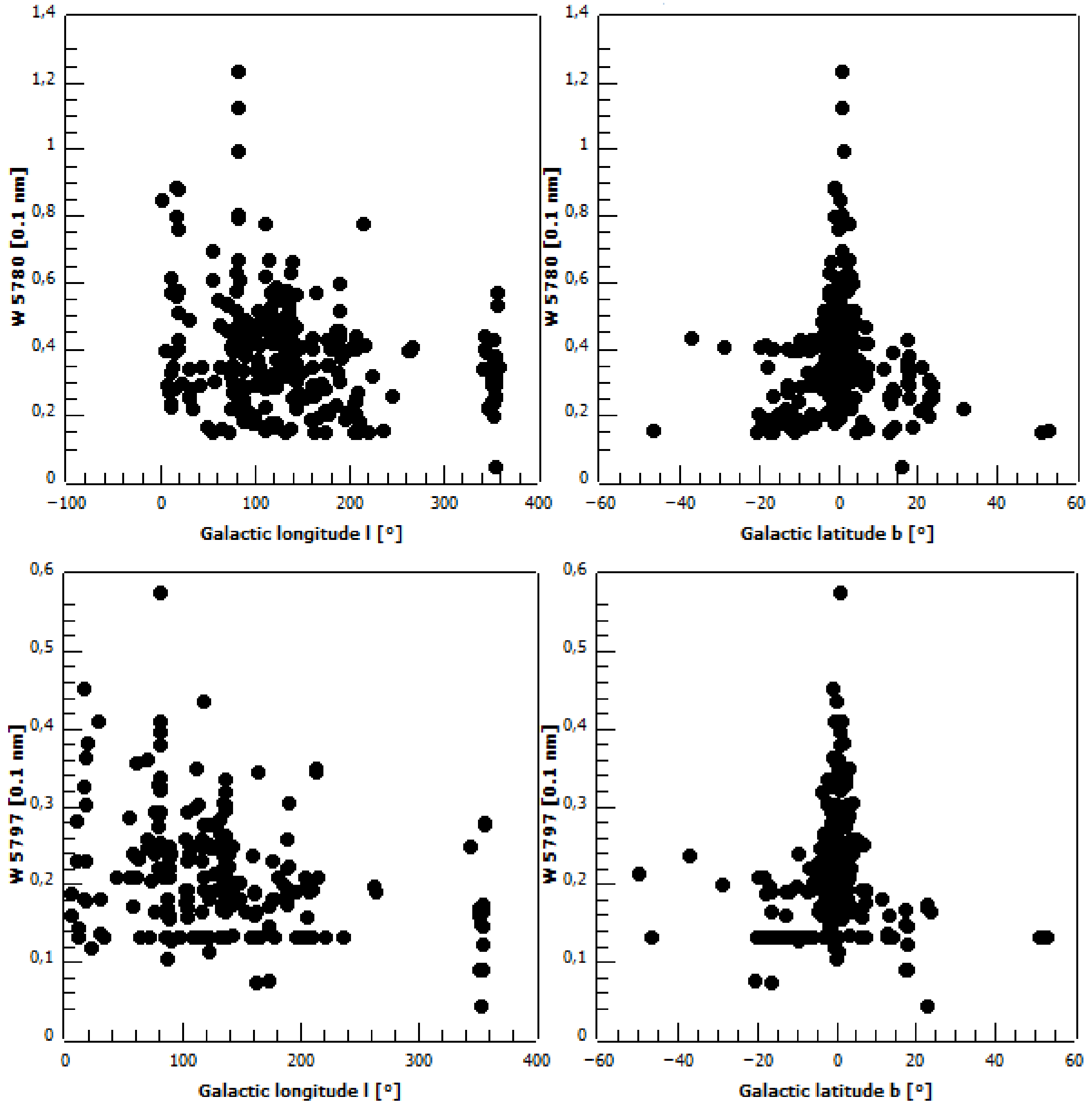


Figure 4.12: Correlations between W5780, Galactic longitude l (top left), Galactic latitude b (top right) and W5797, Galactic longitude l (bottom left) and Galactic latitude b (bottom right); Snow et al. (1977).

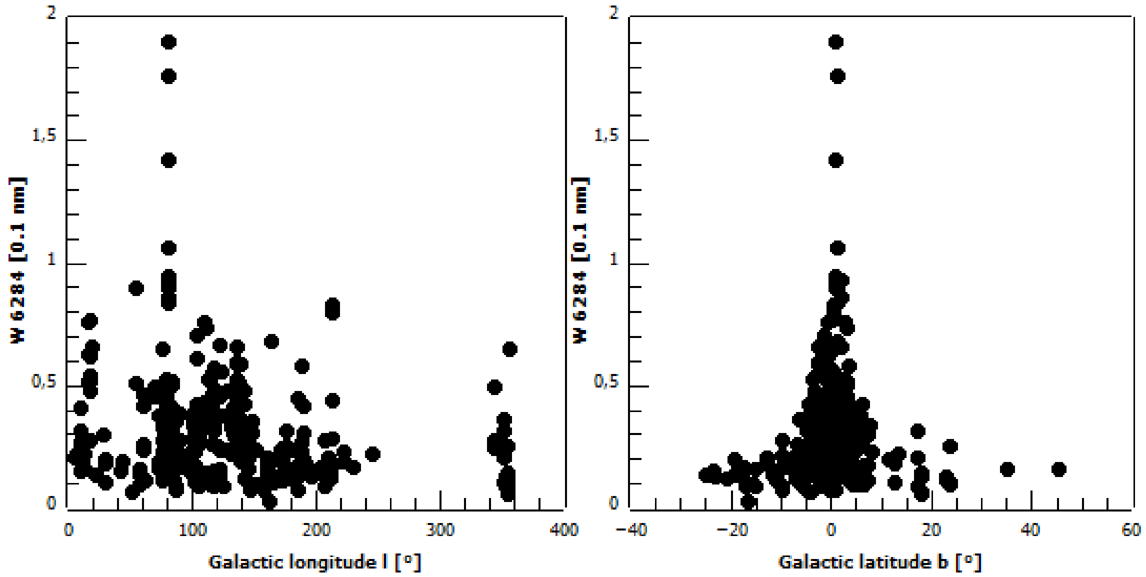


Figure 4.13: Correlations between W6284, Galactic longitude *l* (left) and latitude *b* (right); Snow et al. (1977).

4.4 DIBs and Colour Excess

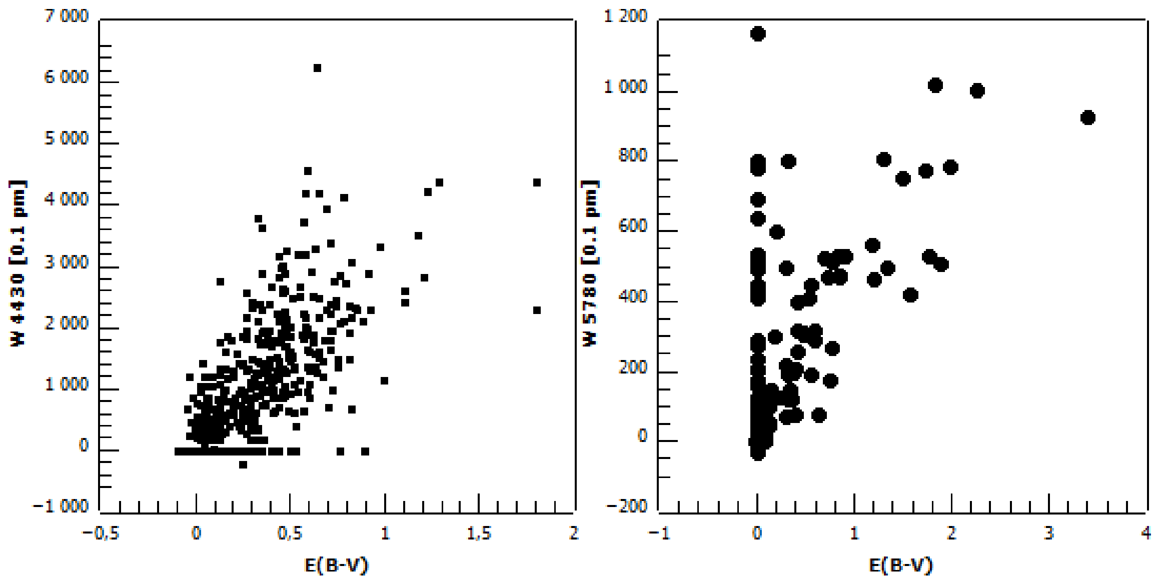


Figure 4.14: Correlations between W4430 (left), W5780 (right) and colour excess $E(B-V)$; Guarinos (1988).

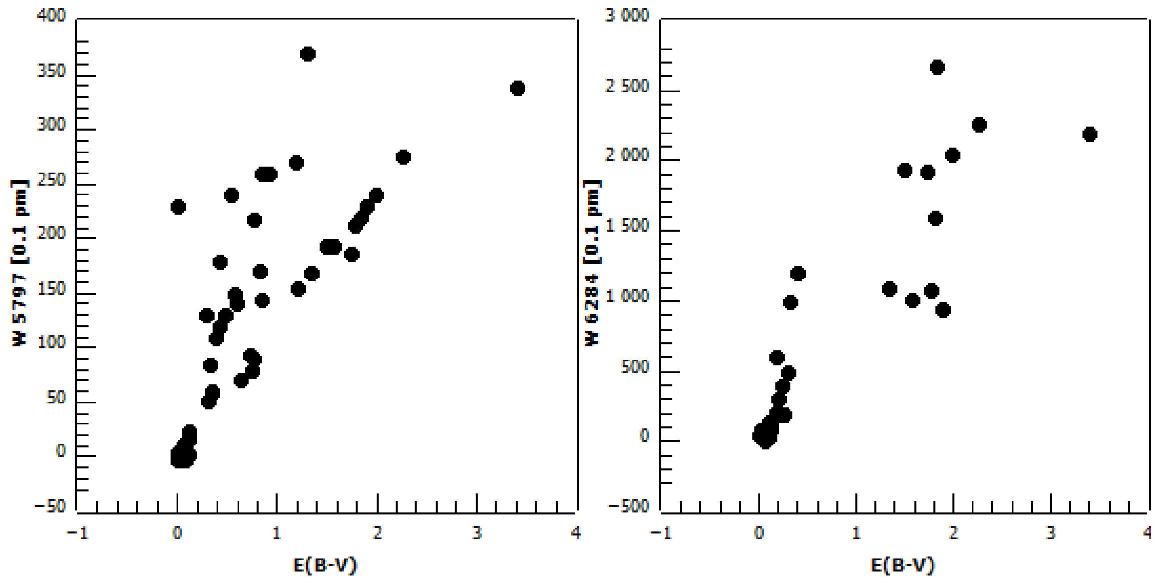


Figure 4.15: Correlations between W5797 (left), W6284 (right) and colour excess $E(B-V)$; Guarinos (1988).

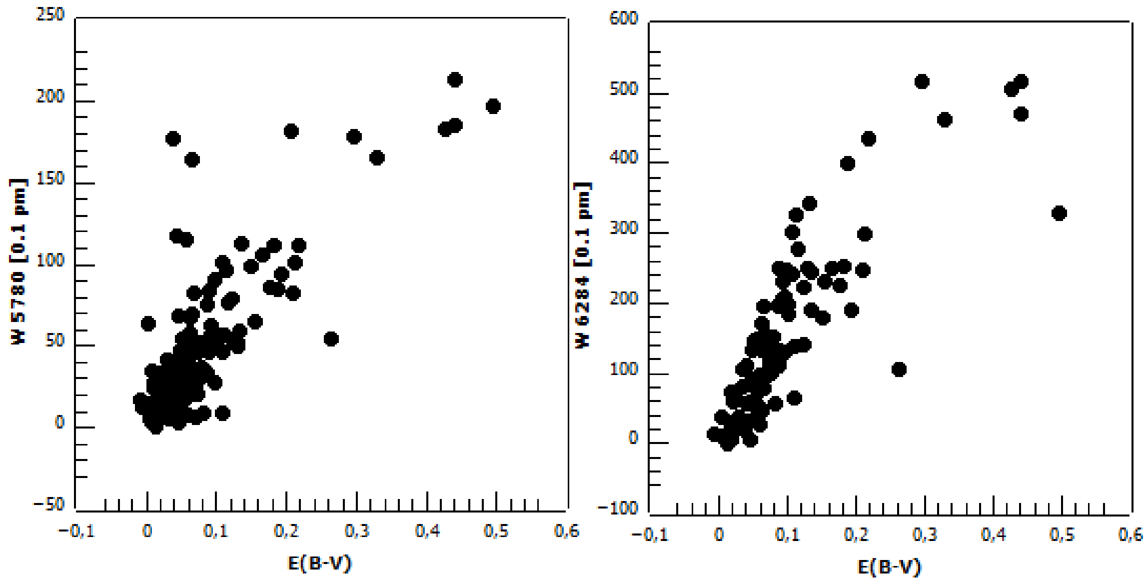


Figure 4.16: Correlations between W5780 (left), W5797 (right) and colour excess $E(B-V)$; Raimond et al. (2012).

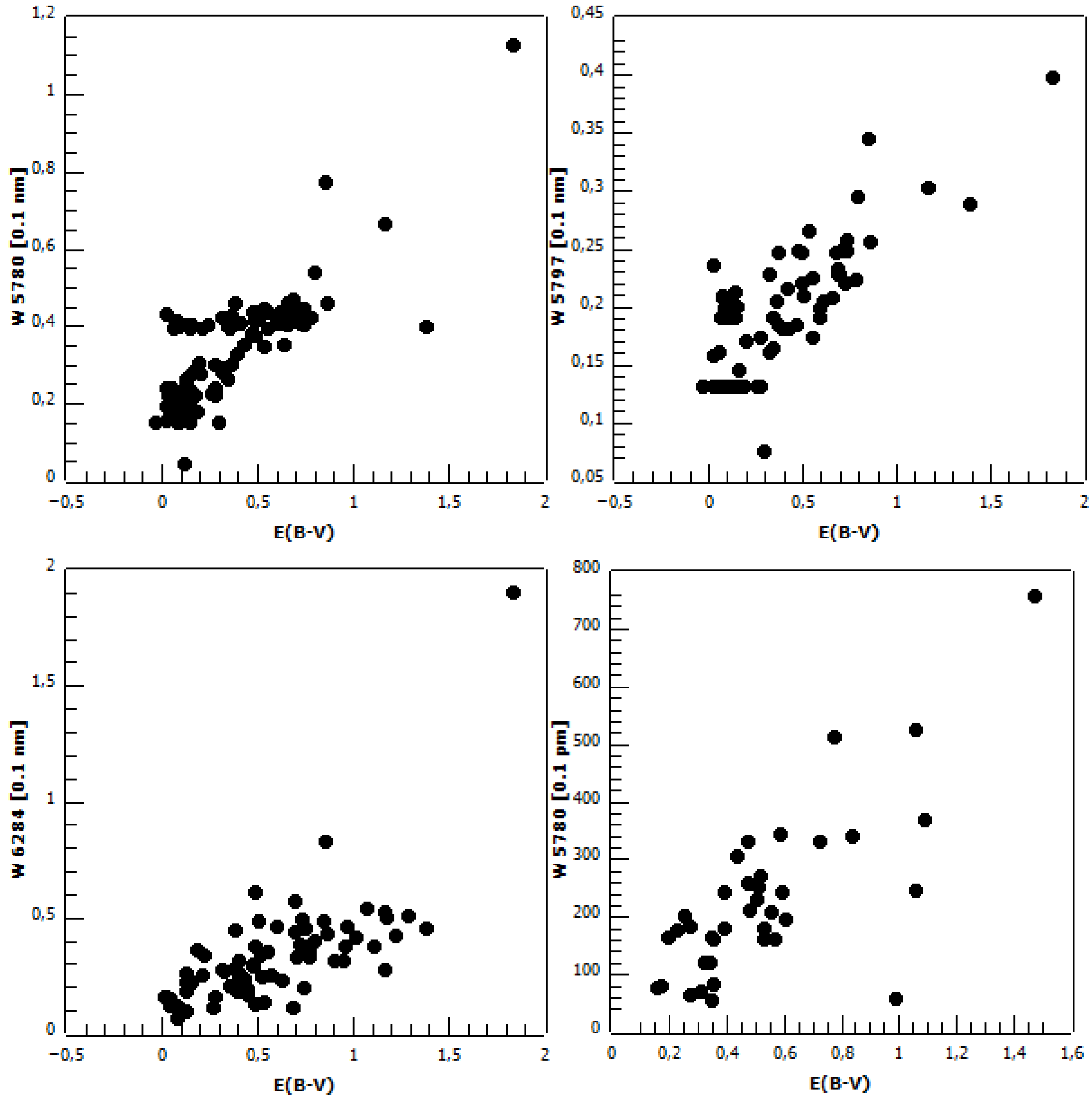


Figure 4.17: Top left, top right and bottom left represent correlations between three equivalent widths and colour excess $E(B-V)$; Snow et al. (1977). Correlation between W5780 and colour excess $E(B-V)$ (bottom right); Xiang et al. (2011).

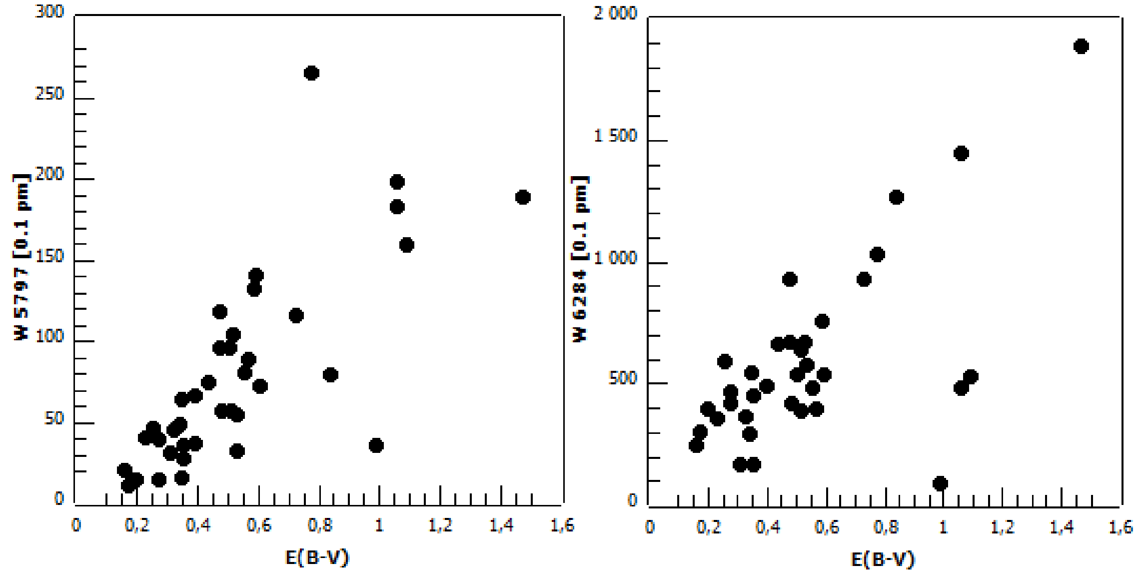


Figure 4.18: Correlations between W5797 (left), 6284 (right) and colour excess $E(B-V)$; Xiang et al. (2011).

4.5 DIBs and Metallicity

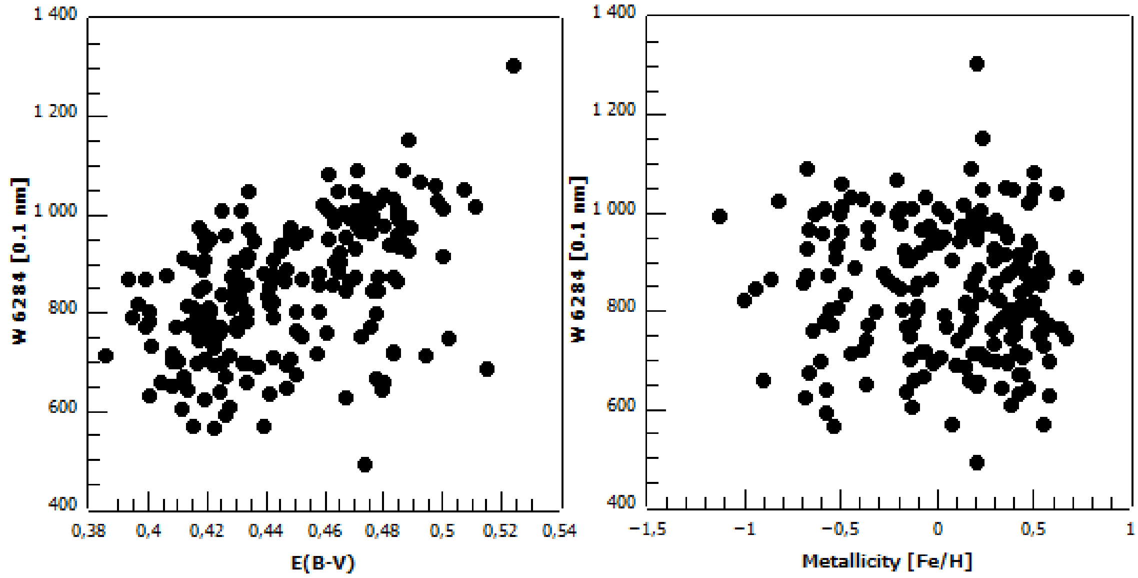


Figure 4.19: Correlations between W6284, colour excess $E(B-V)$ (left) and metallicity [Fe/H] (right); Chen et al. (2013).

4.6 Discussion

Athough many plots are too pour to provide any useful information, they provided at least an option to compare richer plots with them. We shall now discuss the results following from the correlations, baring in mind that we are looking only at the Solar neighbourhood.

- There is an expected correlation between equivalent width of DIBs and colour excess $E(B-V)$. Points, however, do not seem to follow the same line, only a specific direction. It implies that for any observed star there is a certain range of possible strengths of the bands. This effect could be caused by the uncertainties of widths but may as well be related to the interstellar medium itself.

- Correlations with galactic coordinates x, y, z suggest that the value equivalent width of DIBs is highest around 150 pc towards the centre of the Galaxy (x). It does not seem to vary much in the direction of movement of the Sun (y) and as we expected, the strength of the bands peaks at the centre of the Galactic disc and the value falls down as we go further away in both directions (z).

- Galactic latitude seems to follow the same trend as the z coordinate. Understanding the correlations with Galactic longitude is more difficult. The strength of the bands reaches its maximum at approximately 80°, 140° and 300° but there also are apparent gaps with centres at 50° and 320°. As we get further from the Sun, the strength of the bands slowly drops. There seems to be a quick jump from 0 pc to 200 pc in data from Raimond but this can be easily explained by the effect of choice.

- A small problem arises with the correlation with metallicity. Although the plot does not seem to show any correlation with 6284 Å band, we cannot certainly confirm this result. It is due to the fact that when we look at the correlation with $E(B-V)$, we can see that the values of metallicities were found only for stars with small variety of colour excess and this may highly bias the result.

Observations towards many more stars are still required in order to confirm some of these results. Correlations with colour excess look peculiar and are different from each other. A possible explanation would be the effect of choice.

Conclusion

In this thesis, we were studying the properties of several diffuse interstellar bands in the Solar neighbourhood. The goal was to find relations between different properties of observed stars and the strengths of DIBs. Since we were not able to make our own observations due to the technical requirements, we studied the data from other different research teams.

First we had to choose such bands, from which it would not be difficult to determine their equivalent widths and would appear in most spectra. Four different strongest bands satisfied these conditions, allowing us to find many previous works about them. Comparing them with each other, we found that these four DIBs most likely do not share the same carrier. They, however, followed the same pattern and it implies that they share at least the same region of origin in the interstellar medium.

Correlations of the equivalent width with the colour excess $E(B-V)$ shows an expected linear relation. It follows from the correlations with Galactic coordinates that the bands originate from the interstellar medium, since the strength of the bands falls down as we get further from the Galactic disc within which is the medium concentrated. The plots also provide a very good map of the Solar neighbourhood in the terms of Galactic longitude and latitude, and only a poor quality map in the terms of Galactic coordinates x, y and z. We found a very interesting behaviour of the Galactic longitude which should be compared with the extinction maps in the future. Finally, we have seen that the band 6284 Å does not depend on the metallicities of observed stars.

We conclude, that we were able to find some properties of the diffuse interstellar bands concerning the Solar neighbourhood. Our results ought to be considered in the future observations and we encourage other teams to verify them.

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