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ASTRONOMY

BACHELOR THESIS

The peculiar FIR emission of 3C 318

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1 Introduction

This bachelor thesis will treat the peculiar far-infrared (FIR) emission of the quasar 3C 318. 3C 318 has been noted to be a powerful high redshift infrared source by far-infrared and sub-millimeter (submm) studies. However, recently obtained Herschel data reveal that a pair of interacting galaxies about 18 arcsec west of 3C 318 also has strong FIR emission. This emission would contribute to the total flux of 3C 318 measured in the earlier studies with poor resolution. To assess the nature of the galaxy pair, an optical spectrum has been obtained in order to determine their redshifts. This redshift was then be used with photometric data to determine the contribution of the interacting pair to the FIR flux of 3C 318. Section 2 will provide some background information on Active Galactic Nuclei (AGN), in particular quasars and 3C 318. Section 3 will provide information of how the spectrum was obtained, the analysis of that spectrum and its implications for 3C 318. In Section 4 the conclusions of this thesis will be presented, followed by section 5 containing the appendix with details of the data reduction.

2 Background

3C 318 is a radio-loud quasar and thus an AGN. There are many different types of AGN, but all of them are powered by the same physical phenomenon, an accreting supermassive black hole (SMBH). To better understand the unusual FIR emission of 3C 318 some background information will be provided on these supermassive black holes. Section 2.1 will provide some information on AGN in general, how they are powered and what types there are. Section 2.2 will go a bit more into detail considering the infrared (IR) Spectral Energy Distribution SED of a quasar. This is followed by information on the quasar 3C 318 and the excess FIR emission of 3C 318, in section 2.3 and section 2.4 respectively.

2.1 Background on AGN

AGN are extremely luminous objects and because of that they are amongst the most distant objects visible to us. AGN are interesting as they allow us to look into the past of the universe and to have a glimpse of how the universe used to be. Unfortunately this glimpse is most likely highly biased. After all an active galaxy might be visible at high redshift but that does not mean it is typical for galaxies at high redshift.

The luminosity of AGN needs to come from somewhere. So far the most accepted model for the production of enough energy for AGN to be so luminous, is accretion onto a SMBH. If the central black hole manages to accrete enough gas and dust it will become an AGN. It is suspected that many galaxies have gone trough an AGN phase at some point in their life but nowadays just do no longer accrete a sufficient amount of mass to be an AGN. Surrounding the SMBH is an accretion disk, this disk is heated up by a combination of different dynamical, thermal and viscous processes. These processes all contribute to the enormous luminosity of the quasar, but the main source of energy for this model is the release of gravitational binding energy. The mass to energy factor (ϵ) used to represent the percentage amount of gravitational binding energy released in the form of energy is not well known. Generally the value 10% is used for (ϵ) but this depends a lot on the conditions of the black hole, like its spin. (McNamara 2009). In comparison, the proton proton chain has an efficiency factor of about 0.7%.

Furthermore, accretion onto a black hole would explain the different types of AGN with one theory, effectively combining nearly all the different types of AGN into one single natural phenomenon. Using this theory seemingly different types of AGN would be unified. The AGN type would depend on the host mass, the AGN luminosity, the radio luminosisty and, as can be seen in figure 1, the angle along which the object is viewed. The subject of AGN unification is reviewed in Urry & Panovani (1995).



Figure 1: Schematic depiction of a radioloud AGN. The image depicts the most important internal regions of the AGN. Some radiation has a preferred orientation or will be blocked by dust or gas, therefore looking at the AGN form a different angle will give the observer different SEDs depending on the observers orientation with respect to the AGN. AGN luminosity and the mass of the host galaxy also play a role in the SED of the AGN. Image credit: Urry & Padovani (1995)

Most of the energy generated in AGN is generated in the central regions of the accretion disk below about 100 times the Schwarzschild radius (R_s) . The surrounding regions get heated by this energy as it cannot escape directly because of the high opacity of the medium. The region surrounding the supermassive black hole consists of multiple regions each responsible for different types of emission. The blue bump or ultraviolet (UV) bump is generated mostly by the accretion disk itself, the accretion disk creates its radiation not just by thermal emission but also by non_thermal means. The source of non-thermal emission is either synchrotron radiation, bremsstrahlung or inverse Compton scattering. All these factors together make that this region is extremely hot, even with adequate cooling the temperature cannot fall below 10^4 K (Rees (1978) accretion and the quasar phenomenon, Section 3.2). This results in an excess of UV emission creating the blue bump. The obscuring torus surrounding the accretion disk on the other hand is much cooler and responsible for most of the infrared and far infrared part of the spectrum by means of simple thermal methods like classical excitation. An overview of the SED of an AGN can be seen in figure 2.



Figure 2: An overview of the emission spectrum of an AGN. This image is in no way representative of all the different types of AGN, however shows features that many of them contain, like the blue bump created by thermal emission from accretion or, more interesting, the IR part of the SED created by the dusty torus of the AGN and star formation in the host galaxy. (Image credit: Anuradha Koratkar & Omer Blaes, The ultraviolse and optical continuum emission in active galactic nuclei: The status of accretion disks. 1999 NED)

One trend observed around AGN is that AGN are more likely to have a companion galaxy, for example about 15 % of Seyferts have companions compared to about 3 % for normal galaxies. (Jones & Lambourne, An Introduction to Galaxies and Cosmology) This would make sense as the tidal perturbations destabilize the primary disk resulting in the self-gravity of the disk taking over. This in turn then causes gravitational instabilities that result in dust and gas being funneled down towards the SMBH. (NED, Combes, Fueling the AGN Section 6.2) Star formation can also be boosted or induced by the presence of a companion at high redshift for high mass galaxies. This is the case as for high redshift the number density of galaxies is larger that that it is now and the probability of interaction is dependents on the number density of galaxies as concluded by Ideue et al. (2013).

The SED of an AGN differs depending on the type of AGN observed. Differences in the AGN types are created by the orientation of the AGN. The different types of AGN are¹:

• Seyfert galaxies:

This AGN type has two main sub classes defined as Seyfert 1 and Seyfert 2. Seyfert 1 galaxies have broad permitted lines, like HI, HeI and HeII, and narrower forbidden lines like O[III]. The spectral lines found in Seyfert 1 galaxies are much broader than the emission lines found in normal galaxies. A Seyfert 2 galaxy only has narrow emission lines. Some Seyfert like galaxies show both narrow and broad lines and are defined as the Seyfert 1.5 class.

• Radio galaxies:

As the name may imply radio galaxies emit strongly in the radio part of the spectrum. Radio galaxies have subclasses named broad line radio galaxies or BLRG for short and narrow line radio galaxies, or NLRG for short. There are multiple differences between the BLRG and NLRG. Just like with the Seyfert galaxies the width of the spectral lines makes a difference, with the BLRG having both broad and narrow lines and the NLRG having only narrow lines. Another difference is that BLRG have some, if weak, polarization while NLRG have no polarization at all.

• Blazars:

Again just like with the previous types of AGN blazars are split into two smaller sub classes, BL Lacs and Optically Violent Variable quasars or OVV quasars. Both of these groups have strong radio emission, strong polarization, and a rapid variability in their emission lines and continuum. The two classes are nearly the same expect that BL lacs have nearly no emission lines and are less luminous than the OVV quasars, which do display broad emission lines.

• Quasars:

Just like the other AGN classes, quasars can be split into two sub classes, these being radio-loud quasars (QSR) and radio-quiet quasars (QSO). The difference between these two lies in the strength of the radio emission and the polarization. The radio-loud quasars having somewhat more polarization and more radio emission than the radio-quiet quasars. The object 3C 318 is a radio-loud quasar.

• Others:

The following types may contain an obscured AGN at their center, but could also be heavy starbursts. The first of these types being the ULIRGs or Ultra Luminous Infrared Galaxies, these objects may be dust enshrouded quasars or they could also be star forming galaxies. The second type of these two are LINERs or Low Ionization Nuclear Emission-line Regions, LINERs have low luminosity in their core but have strong emission lines like OI and NII. Their spectrum looks similar to that of the low end of a Seyfert 2 class.

 $^{^1\}mathrm{AGN}$ types as found in: An Introduction to Modern Astrophysics by Bradley W. Carroll and Dale A. Ostlie

2.2 Quasar IR SED components

In this thesis the emphasis is on the FIR emission of 3C 318. It is therefore important to have a look at what the FIR SED of a quasar looks like in order to make any meaningful conclusions about the FIR SED of 3C 318. Podigachoski et al.(2015) provide a median SED of a sample of 25 QSRs and 37 radio galaxies (RGs) obtained by Herschel and Spitzer and should provide a representative selection for QRSs at the high redshift of 3C 318.

Visible in the figure 3 is that radio galaxies and radio-loud quasars have a cutoff at the same wavelength as the star forming galaxies at the same redshift in the far infrared regime. This component is created by dust heated by star formation in the host galaxy of the AGN. The temperature of this cold dust is generally about 40 K and is heated on the scale of kilo parsecs. The fact that both radio galaxies and the radio-loud quasars have the same FIR cutoff as star forming galaxies at the same redshift leads to the conclusion that AGN must also be star forming. There tend to not be any major dust clouds below 40 K in star forming galaxies resulting in the cutoff in the spectrum.

Besides the star formation component there are a number of other major components for the infrared regime of AGNs. One of these components is created by old stars from the host galaxy. This component is generally found peaking near 1 to 2 microns and is overall less luminous than the other components but not unimportant in the case of radio galaxies. However, in the case of quasars this part is completely outshone by the 1300K component and can thus be ignored. The 1300K component is in the case of quasars one component used to account for the emission of hot dust. The last major component is the torus, this warm dusty torus is heated by the AGN and peaks in the mid infrared.

These components together make up most of the IR regime of an AGN. Not all of them will be equally visible from every angle, for example the 1300K component is present in radio galaxies but is not dominant. However, if one were to look at the same object from a different angle the components that weren't visible at first, like the old star component in quasars, will be observable.



Figure 3: Median SEDs for the radio galaxies (dashed red) and quasars (dotted blue) detected in at least three Herschel bands. It also contains the SED of z < 2 star forming galaxies (solid yellow) from Kirkpatrick et al.(2012). Shades areas, red for radio galaxies and blue for quasars, correspond to the associated 16th-84th percentile ranges. The difference in the mid infrared emission is caused by the orientation of the torus. QSRs are looked at face on meaning that we can see the hot part of the torus, whereas RGs are seen from the side meaning that the hot part of the torus is obscured. The fact that the different types of AGN follow the same slope towards high wavelengths is prove for the AGN unification theorie. Image source: Podigachoski et al.(2015)

2.3 Background on 3C 318

The object 3C 318 is a radio loud quasar at redshift z=1.574 and is known to have a high amount of FIR luminosity. As is visible in figure 4 the SED of 3C 318 follows the models for the torus and star formation to a high degree. When the SED reaches the far-infrared cutoff on the other hand the models can no longer account for the flux observed. Willott et al. (2000) had to fit a 100K isothermal dust component in order to account for the FIR and this was still not enough to account for the FIR flux. This would imply that if all the FIR flux found 3C 318's SED came from 3C 318 the quasar host would contain very large quantities of too hot dust. The dust emitting at this wavelength is heated by star formation, however star formation heating generally heats the dust up to 40K and thus cannot account for the required 100K in order to fit the given flux. Meaning that either 3C 318 had a lot more star formation that is usual for AGN or not all of this FIR luminosity is from 3C 318 itself. The pair of galaxies at approximately 18 arcsec to the west of 3C 318 that are treated in this thesis are suspected for adding to the FIR emission of 3C 318 at low resolution. Using Herschel data it was found that this pair of interacting galaxies is bright in the infrared. The pair of galaxies treated in this thesis might not be the only object that contributes to the FIR luminosity found in previous low resolution studies of 3C 318, as there seem to be other galaxies, much closer to 3C 318, that might also contribute to its FIR luminosity. To estimate how much this pair of galaxies might be contributing to the FIR found in 3C 318 with low resolution studies



Figure 4: FIR SED of 3C 318. The 1300K component is a black body component added to account for the hot graphite dust close to sublimation temperature. The temperature of this component was fixed at 1300K. The torus component is the part of the SED that is created by emission from the torus, this torus is heated by the AGN. SF stands for the star formation component, this component is created by emission resulting from the formation of stars in the host of the AGN heating the surrounding dust to temperatures of about 40K. The black line represents the total fitted SED curve for 3C 318. The SPIRE 350 and 500 micron values have been left out of the plot as they are contaminated by an external source and will be added in figure 6. Image source: Podigachoski et al.(2015)

it is vital to have a decent estimate for the redshift of this interacting pair.

Therefore for this thesis a new observation has been done on the night of 2014-02-06 using the ACAM on the William Herschel Telescope at the La Palma Observatory. A spectroscopic image was taken using a slit of 1 arcsec width at an angle of 63 degrees, see figure 5, so that the spectrum would not be contaminated by 3C 318 and thus only the spectrum of each of the galaxies would be obtained. With the spectra provided by this observation the redshift of the interacting pair of galaxies near 3C 318 will be determined using IRAF.



Figure 5: SDSS image of 3C 318 with the pair of interacting galaxies about 18 arcsec to the right of the center of the image. The area between the red lines represent the slit used to obtain the spectrum.

2.4 The excess FIR emission of 3C 318

In the paper by Podigachoski et al. (2015) the data points for 350 micron and 500 micron where left out as they where contaminated by, most likely, the interacting pair of galaxies 20 arcsec to the west of 3C 318. Another data point can be found at 850 micron, this data point was noted in Haas et al. (2006) to be contaminated by synchrotron radiation. According to Haas et al. the synchrotron radiation contribution is 3.53 mJy. After removing the synchrotron radiation the difference between the data point and fitted curve for 3C 318 falls within range of the error bar for the data point. However, the error bar only barely reaches the fitted curve at a value of $1.15 \cdot 10^{-14} \ ergs^{-1}cm^{-2}$ meaning that if there is any contamination by the interacting pair it is very small. This is to be expected as the angular resolution of Max-Planck-Millimeter-Bolometer or MAMBO used to obtain the 850 micron data point is only 15 arcsec. (Haas et al. 2006) Meaning that, besides the antenna, most of the interacting pair is not within the beam of observation, but contamination of the antenna alone is small compared to the contamination of the 350 and 500 micron observations, explaining why the 850 micron data point only adds so little to the FIR emission of 3C 318. The 350 micron beam, on the other hand has a beam size of about 25 arcsec for its full width half max (FWHM) and would thus contain nearly the entire pair of interacting galaxies, even if the contribution is not 100%. The 500 micron beam has an angular resolution of about 37 arcsec and would thus envelop the entire interacting pair. This point would thus be the most contaminated and therefore the best suited to calculate the luminosity of the interacting pair. (Barlow et al. 2010)



Figure 6: Contaminated SED of 3C 318 containing the uncontaminated SED of 3C 318 and 4 extra data points, one for 350 micron, one for 500 micron and two for 850 micron. The 350 and 500 micron values were obtained in private conversation with Podigachoski and the 850 micron value was obtained from Haas et al. (2006). These data points where contaminated and thus left out of the uncontaminated SED. The red square at observed wavelength of 850 micron is the expected value of the data point when the contribution of synchrotron radiation has been accounted for. Also note that the errors of the last 3 data points are not represented by the dot of the figure. For the error see table 1.

Wavelength	Rest wavelength	Frequency	Flux density	Flux
(μm)	(μm)	(10^{11} s^{-1})	(mJy)	$10^{-13} (\rm erg \ s^{-1} \ cm^{-2})$
350	136.19	8.57	34.7 ± 6.2	2.974
500	194.55	6.0	26.7 ± 6.3	1.602
850	330.74	3.53	$7.8{\pm}1.0$	0.275
850	330.74	3.53	$4.3{\pm}1.0$	0.151

Table 1: Contaminated data points with values

The fourth row of table 1 contains the corrected value for the 850 micron emission after the synchrotron radiation has been subtracted. The difference between the data points and the point at the same wavelength on the fitted curve for 3C 318 is 7.4 mJy for 350 micron, 13.1 mJy for 500 micron and 1.27 mJy for 850 micron. This excess amount of FIR emission would most likely be caused by the interacting pair of galaxies about 20 arcsec west of 3C 318. In the next section a spectrum will be extracted for the interacting pair in order to determine its redshift. This can then be used to determine its luminosity in order to say something useful about the nature of this pair.

However, the values in table 1 pose a problem. The difference between the fit at 350 microns and the observed value at 350 microns is lower than the difference between the fit at 500 microns and the observed value at 500 microns. When one looks at the way the dust component heated by star formation is shaped one can see that having a lower value for the 350 micron than the 500 micron might pose a problem for a fit of 40K dust emission trough these points. Basically that would mean that this dust component would be cooler than the 40K star formation component, however it is more likely that there is a massive error bar around the 350 micron data point. To check these values a fit was done for the Photoconductor Array Camera and Spectrometer (PACS) values at 70 and 160 microns, with the 70 microns having a flux density of 221.2 ± 3.8 mJy and the 160 microns having a flux density of 277.5 ± 6.1 mJy. Fitting the 70 and 160 micron values to a dust emission of 40K shows that the 70, 160 and 500 micron are all relatively well positioned on the curve of that fit and that it seems to be the 350 micron emission that falls short, what exactly is going on here is not yet known. But it might be an error somewhere with the measurements. This can be seen in figure 8.



Figure 7: This image contains the 70 micron PACS value for the interacting piar. As is visible the pair is blended and it is thus not possible to tell how much emission comes from each. Image source: private communication with Podigachoski.



Figure 8: SED of the PACS values of 70 and 160 microns fitted to a 40K dust emission for star formation heated dust. the 350 and 500 micron values have been added to see whether they would actually fit or not, it seems from the plot that the 350 micron emission does not fit the expected flux, why this is is not yet known. Image source: private communication with Podigachoski.

3 Spectrum analysis and results

The program IRAF was used to obtain the spectrum for the interacting pair of galaxies. Only bias and flat frames have been taken which means that it was not possible to do a correction for dark current that would have removed any thermal noise in the frames. Section 3.1 will elaborate of how the spectrum was derived followed by section 3.2 with the results this spectrum provides. In section 3.3 there will then be a closer look at what this means for 3C 318 and the interacting pair of galaxies close to its projection.

3.1 Obtaining the spectrum

This part of the thesis will treat the analysis of the data considering the interacting pair of galaxies 18 arcsec to the west of 3C 318. Section 3.1.1 will explain in basics how to extract instrumental errors from the data, section 3.1.2 will explain how to calibrate a wavelength range to the data and section 3.1.3 will explain how to extract the spectrum.

3.1.1 Error subtraction

In order to obtain the spectrum the first thing that must be done is to correct the acquisition image to the bias and the flat. The bias is an instrumental error that is roughly the same in each image made, basically read noise and the offset signal for CCDs. The bias can be subtracted by creating a number of different bias frames and then combining these into a single file. In the case of IRAF this was done using the command *zerocombine*. This then combines the bias frames into one master bias frame by taking the, in this case median, or average of the pixel values provided per pixel. This file is then subtracted from the acquisition image using the command *ccdproc* and applying this command to all images that require the bias to be subtracted. This task can be used for many different types of corrections but for now only the bias is required. This task has to be applied to the flats, the arc files and the acquisition image.

After correcting the flat files for the bias, the next step was to combine these as well and then to normalize them. This is done as flats frames can be used to account for the pixel sensitivity. That way oversensitive pixels that would otherwise give fake values are then corrected for to get a better overall image. The combining of the flat files can be done using the command *flatcombine*. When this was done the combined flat has to be normalized using the command *fit1d*. Now replace any weird values like extremely high numbers or negatives in the normalized flat and replaced them by one. This was done using the command *imreplace* and all values below 0.2 and 1.8 were replaced by 1. Then the acquisition image was divided by the normalized flat to account for the pixel sensitivity using the command *imar*. This has to be done for all images that are to be used, as in both acquisition images and arc lamp files. When this is done any instrumental errors have been removed from the images and so the wavelength calibration can begin.

3.1.2 Wavelength calibration

The arc lamp and the objects have both been measured by the same CCD, this can be used to link the wavelength range of the arc lamp to the wavelength range of the object. Since the prominent elements in the arc lamp are known they can be used to determine the location of each wavelength in the object.

Using the OI line at 5577 Angstrom and the Na1d line at 5899 Angstrom the average wavelength per pixel was calculated to be 3.42. This may not work to determine the wavelength of skylines that are far apart as the wavelength distribution is not linear, but on close scale the change of wavelength is nearly linear so it is a good start.

Once one has a general idea of what line is what wavelength the command *identify* can successfully identify the rest of the lines. When this has been done to a satisfactory degree apply the command *reidentify* on the arcfile used to derive the wavelengths of the arclines. Repeat this but now with the command *fitcoords*. This will apply the new coordinates, as in wavelength, to the axis of the image. Now all that is left to calibrate the ID spectra is to repeat the previous steps for the acquisition image as well. To do so use the command *transform*. This task will then add the calculated wavelength range to the object image. This should now be visible in ds9 in the second panel to the right of WCS. If there are any cosmic rays in the part of the spectrum be sure to remove these using the *imreplace* command to make sure they do not pollute the spectrum.



Figure 9: Skylines of the object image, this image combines all columns from column 200 to column 1800 and plots the average value for each row in the y axis. when compared to an image of the night sky containing the skylines it is obvious that this image contains the night sky.



Figure 10: This plot contains emission lines of the cune and cuar spectrum for an cune cuar arclamp with a grating of 600. This was then used to find what emission lines from the arcfiles fit these values.

3.1.3 Spectrum extraction

The final step to create the spectrum was to apply the *apall* command. This command is huge and contains many aspects. Generally most of the parameters

that one needs to change need to be changed to be consistent with parameters used in previous commands. In this case there are 3 objects in the slit meaning one needs to set 3 apertures for appal to select them all, even if one of the objects is not useful to us. Then apall was ran and the apertures re-sized so they would contain the entire emission from the galaxy but would not overlap. Then the background was selected by selecting a part of the spectrum close to the object lines in order for the background to be as similar as possible to the background contained in the object lines. Make sure the selected background does not contain any cosmic rays as they may mess up the spectrum. When done with the selection of the aperture and background safe these settings by quitting and answering with yes. This will show a screen containing the location of the object line. Delete any points that deviate too much and continue. At this point the spectrum is created and one can move on to determine any emission lines.



Figure 11: The acquisition image after having received the wavelength calibration and being cut to a more useful size.



Figure 12: Spectrum of the east galaxy in the interacting pair. The emission lines deducted from the acquisition image are highlighted by arrows pointing at them.



Figure 13: Spectrum of the west galaxy in the interacting pair. The emission lines deducted from the acquisition image are highlighted by arrows pointing at them.

3.2 Determining the redshift and luminosity

To say something about the luminosity of the pair of interacting galaxies the flux and the distance need to be known. The flux is derivable from the SED of 3C 318 by assuming all the flux difference between the model and the actual measurement to be produced by the pair of interacting galaxies, this will provide a flux for the pair of interacting galaxies. To enhance the precision of this measurement this should be done for all 3 data points. The next thing needed is

the distance to the objects, this can be derived using the redshift of the objects. To determine the redshift one needs to link the observed emission lines to an emission line in rest. If one only has one emission line determining the redshift is not possible using this method. However, the spectrum obtained reveals two emission lines, allowing these lines to be linked to a wavelength in the rest frame. A good way to start is with an educated guess. As often the brightest emission line is the Hydrogen alpha line this is a good place to start. Using that the brightest line is Hydrogen alpha, one can calculate the redshift and see if any other object lines now link to other well know emission lines.

If the calculated wavelength does not match that of an emission line then the redshift is wrong. In this particular case the sky subtraction is not very well done and thus many object lines might be hidden behind these lines. In the spectrum of the east galaxy of the pair, two lines are visible. One near 5007 Angstrom and one near 6727 Angstrom. At first it was tried to fit these lines to Hydrogen beta and Hydrogen alpha, respectively. However, in that case the redshifts are not the same.

Since the educated guess didn't give any answers the next option is to try any emission line and see if the other emission line gets a match at the same redshift. After trying many different combinations all at low redshift, (below 0.1) higher redshifts where tried. With the help of Prof.Dr Scot Trager the redshift was found too. The results are displayed in figure 14. This showed that the wavelength calibration was about 1 Angstrom off near the red part of the spectrum and that the 5007 Angstrom and 6727 Angstrom line are an [OII] of 3727 Angstrom line and an [OIII] of 5007 Angstrom respectively. This gave a redshift of .3434 for the east galaxy. Doing the same for the west galaxy would give about the same value. However the west galaxy's first peak is much broader and thus difficult to correctly estimate. Its second peak is a lot more accurate. The west galaxy has peaks near 5001 Angstrom and 6721 Angstrom. Thus the redshift of the west galaxy would be 0.3423. Using the same program it became possible to also identify the second OIII line, as before this one was just not clear enough to be distinguished from the background. Another line now showing up was the hydrogen alpha line. This line had hidden itself partially below the bad sky subtraction and was thus not easy to detect with the naked eye. However once its position was revealed it was even possible to find part of the line in the acquisition image.

Furthermore as we expect this pair of galaxies to be interacting the difference in redshift of 0.0011, 4.7 Mpc according to NED cosmology calculators 1, would most likely be caused by one of the galaxies moving away from us while the other moves somewhat more towards us. So for the distance to this interacting pair the rounded redshift of .35 will be used. Unfortunately, calculating distance is not easy, specifically towards higher redshifts. Therefore it is important to realize that depending on what the distance is the luminosity will change as well as the luminosity is dependent on the luminosity distance squared. Other factors that come into play are the errors surrounding the redshift. These arise from the width of the peaks and from the the wavelength calibration. The errors in the wavelength calibration will be of order 1 Angstrom and the same order will apply to any read off error. The width of the peaks is a bit larger as the broadest peak is about 10 Angstrom wide so in total the error in the location of the center of the emission lines is ± 12 Angstrom resulting in a redshift varying between .3402 and .3466. Overall it is safer to assume a redshift of about .35, as most of these calculations are not much more than rough estimates with the current data.



Figure 14: Spectrum of the east galaxy. Difference in the fourth decimal of the redshift are neglectable and most likely came from manually moving the emission lines over the spectrum. In the spectrum one can now see the H β , [OII], [OIII] and the H α lines.

With the redshift and flux known all that is left is to calculate the luminosity of the interacting pair. In this case it is assumed that each galaxy is equally bright and thus each galaxy has 50% of the total luminosity.

3.3 3C 318 and the interacting pair



Figure 15: HST image of 3C 318 and the interacting pair. Both 3C 318 and the interacting pair have been highlighted by a red circle. Indicated by a dotted red line in the image is a stretched lob extending from the east galaxy of the interacting pair, this could be an actual antenna as the bands of the SDSS range from ultraviolet to infrared meaning that the emission observed should also contain starlight indicating that this lob contains stars.

So far the interacting pair seem to have something of an antenna, a tail of gas, dust and stars ejected form its galaxy as a result of the merger process with another galaxy, as is visible in figure 15. Having an antenna can have important implications. First of all it would confirm that the objects about 18 arcsec away from 3C 318 are not just interacting but actually colliding. From other examples much closer to us like the antenna galaxy NGC 4038/39 we know that this kind of interaction is likely to trigger starbursts. NGC 4038/39have a SFR of about 20 M \odot yr^{-1} (Zhang, Fall & Whitmore 2001). This star formation in turn is responsible for heating the dust to about 41K, a typical value for starburst galaxies (Stacey et al. 1991). When applying this 41K component to 3C 318 one notices, as is visible in figure 6, that the model does not fit indicating that 3C 318 has too much too hot dust as is typical quasar of its kind. So the interacting pair having an antenna is great as the presence of an antenna indicates high star formation. This starformation could account for the 40K dust emission and could thus be responsible for the excess amount of 40K dust emission found in 3C 318 at low resolution.

4 Conclusions



Figure 16: This figure plots the values of the 70 and 160 micron data points for the interacting pair and the difference between the data points and the star formation fit for 3C 318 for the 350 and 500 micron data points in order to get an estimate of the emission of the interacting pair at those values.

Using IRAF it was possible to determine the redshift of the two galaxies, for calculations a redshift of z = 0.35 has been assumed. The redshift of the galaxies is very close together. From this and from the antenna like structure in photometric images of the galaxy pair we can conclude that the pair of galaxies is indeed interacting. Calculating the luminosity from the area under the fit for the PACS values of 70 and 160 microns at a redshift of .35 gives a luminosity of $1.35 \cdot 10^{12}$ L \odot for the interacting pair. The difference of the observed values and the fit for 3C 318 for 500 microns fit the fit for the PACS values fairly well. On the other hand, at 350 micron the FIR flux does not fit the 40 K SF emission. Using the approximation that each galaxy in the interacting pair is equally luminous one gets a value of 6.7 $\cdot 10^{11}$ L \odot for each individual galaxy. This places them in the LIRG regime of luminosity. This could be expected as this pair of galaxies has an antenna and antenna galaxies tend to also be starbursters just like LIRGs. An example of this is NGC 4038/39 with a SFR of about 20 M \odot yr^{-1} . Using the relation between L_{FIR} and SFR derived by Kennicutt $(1998)^2$ the total SFR in the interacting pair would be close to 233 $M \odot yr^{-1}$. Splitting this SFR over the two galaxies would give a SFR of 115 $M \odot$ yr^{-1} . Compared to the SFR of 20 M \odot yr^{-1} of NGC 4038/39 one can see that this kind of SFR is somewhat high and although SFR of $100 \text{ M}_{\odot} yr^{-1}$ is not unheard of it is more likely that this pair of interacting galaxies might not be the only contributors to the FIR emission of 3C 318. To make any reasonable claims about the SFR of this interacting pair a more in depth study is required with much more accurate data and resolution. This thesis used very rough estimates to calculate the FIR flux of the interacting pair and even rougher estimates to determine their SFR, this would indicate that the SFR will most likely be a lot lower. All in all the interacting pair having an antenna and the [OII] line in its spectrum³ make the galaxies in the interacting pair believable LIRGs and thus a good explanation for the excess FIR luminosity of 3C 318 at low resolution studies.

 $^{^{2}}$ The relation between FIR luminosity and SFR found in Kennicutt (1998):

 $SFR(M \odot \cdot yr^{-1}) = 4.5 \times 10^{-44} L_{FIR}(erg \cdot s^{-1})$ for starbursts.

Most of the FIR used for this calibration falls in the 10 to 120 micron regime although definitions of FIR varies throughout literature. Most other published calibrations lie within \pm 30% of the relation obtained from Kennicutt. This does add a massive error bar to any SFR obtained trough this formula as it is not yet possible to say whether we can apply this relation.

³The [OIII] emission line can be used as a star formation indicator. NED, Michael A. Dopita, Modelling the UV to sub-mm SED of starburst galaxies, Section 2.



Figure 17: Astronomy picture of the day of N4038/39. Image source: Astronomy picture of the day 2015 February 12

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6 Appendix

For more in depth information on IRAF the text of a beginners guide to IRAF is advised.

Notes on the IRAF commands:

- To edit the parameters of a command type epar followed by the name of the desired command.
- For zerocombine the median was used, this will exclude any very deviant values and give a more accurate representation of the real bias.
- For flatcombine the median was used, same reason as for zerocombine plus consistency is important, especially when it comes to fitting parameters.
- For ccdproc set all other corrections to no and only zerocor to yes. The flatcorrection will be done manually and we have no dark to correct for.
- For imar, insert the name of the file you want to divide then a forward slash followed by the name of the file you divide by followed by the name you want for your corrected image.
- For identify: In this command one assigns each peak that one knows the value of its corresponding wavelength. Then next step is to fit these values to the arclines by simply pressing "f". When this is done a screen containing the residues will appear. Now one needs to decide what values are good and what values are not. After deleting any values that are too far off go back to the screen containing the selected peaks, by pressing "q", and re-select peaks. Alternatively let IRAF pick peaks itself by pressing "e", do check for any peaks that are very low intensity or too close together as they are not very reliable. IRAF will now fill in a value for these peaks by itself. Keep repeating the process of deleting points that are too far off and re-selecting points until adding or removing lines does no longer change a lot for the RMS value. One goal to keep in mind is to try to get a RMS as low as possible with as much data points as possible.

- For reidentify: To check if the values received are in any way good look at the RMS gained for all the different columns. It is okay if this differs for the edges of the plot but if there is too much variation in between then something probably went wrong.
- For transform type name of object image followed by the name for output file and fitnames= name of your calibrated arc. This task will then add the calculated wavelength range to the object image. This should now be visible in ds9 in the second panel to the right of WCS. If there are any cosmic rays in the part of the spectrum be sure to remove these using the imreplace command to make sure they do not pollute the spectrum.
- For apall it is the best to look up a guide as this command contains many possibilities, however for us all we need to do is to focus on the number of apertures and their respective size. Do however make sure that extras has been turned off as we do not need any of the things that it would provide.

Remember if there are troubles with fitting in any command changing the order for the fit may work, but you want to keep the order as low as possible as a high order will fit along everything and will therefore not be very realistic.