

RADIATION ANALYSIS OF NGC 4826

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Subject headings:

1. ABSTRACT

By looking at the cm-wave flux that is emitted from the center of the spiral galaxy NGC 4826, we were able to determine the spectral indices of multiple compact sources located in this region. The spectral index signifies the type of radiation, thermal or synchrotron, and from this we can determine if there were any H_I regions present. Most of the sources appear to be synchrotron sources, probably supernova remnants. One source was discovered to have a positive spectral index and from its thermal flux we estimate that this source is a nebula surrounding a young star cluster containing approximately 130 O-stars with a luminosity of $\sim 2.6 \times 10^7 L_{\odot}$. The nucleus of this galaxy has an unusually high number of supernovae remnants (SNR) as compared to the number of young stars.

2. INTRODUCTION

The spiral Sa type galaxy NGC 4826, also known as M 64, has acquired the names "Black Eye Galaxy" and "Sleeping Beauty Galaxy" due to the dark, prominent dust feature which runs in a SSW direction from the center. This unusual dust feature is related to two counter-rotating disk of gas in the galaxy BW92. It is believed that the gas disks came about through the collision of two disk galaxies and that this gas will ultimately spiral into the center of the galaxy.

However, the center of the galaxy is already most interesting with regards to star formation. Not only are there large amounts of dust and gas in the central region, but there is a large number of SNR (Turner & Ho 1994).

The distance to NGC 4826 is 5 Mpc, the radial velocity is 368 km/sec, magnitude 8.9, right ascension on the order of 12h56m43s, and declination +21d40m60s.

2.1. Thermal Radiation

Thermal emission from HII regions is caused by the interactions of charged, free particles, for example, an electron and a proton. By using a moving reference frame that allows one of the particles to appear at rest, the more massive proton, the electron's trajectory is in a straight line with a velocity, \mathbf{v} . When the particles approach each other, the total power is dominated by the largest acceleration, or when they are closest. We define the impact parameter, b , as the distance from the electron to the proton in the direction perpendicular to \mathbf{v} . Since the particles have different polarities, the electric field of the proton causes a change in direction, and thus an acceleration, of the electron at the closest approach. An accelerated, charged particle radiates and because both of these particles are free, their energy states are not quantized and thus, their radiation is continuous over the spectrum. As the electron loses energy due to its radiation, it decelerates - giving rise to bremsstrahlung, or in German "braking", radiation. The proton's mass is much greater than that of the electron, so its acceleration, and thus its radiation, is negligible compared to that of the electron. And because hydrogen is the most common molecule that an electron would interact with in space, it is a good assumption that this interaction is between an electron and a proton.

While the interaction between electrons and protons yields radiation, that radiation goes through other media before it is received by the observer. Some of it is absorbed while some of it interacts with other particles and then re-emits. The intensity of the emission along a unit path length dx , is seen as

$$dI = -I\kappa dx + jdx, \quad (1)$$

it travels toward the telescope. We define κ as the linear absorption coefficient and j as the linear emission coefficient. The free-free absorption in the radio domain takes into account the number densities of the electrons and protons, N_e and N_p , respectively, the wave frequency ν , as well as the temperature of the electrons T_e , and is approximated for radio frequencies by

$$\kappa_c \approx \frac{0.08235 N_e N_p}{\nu^{2.1} T_e^{1.35}} (pc^{-1}). \quad (2)$$

However, because the radiation must travel the length of the observed cloud, L , that has the intrinsic value κ_c , we combine the two variables in order to gain a value for the optical depth

$$\tau_c \equiv \int_{x_1}^{x_2} \kappa dx \approx \langle \kappa \rangle (x_2 - x_1). \quad (3)$$

Now we have a way of defining how opaque or transparent a medium is to the radiation passing through it, since the reciprocal of τ is likened to the probability that a photon will go from one edge of the nebula, x_1 , to the other, x_2 .

The emission coefficient is coupled to the absorption coefficient in Kirchkoff's law such that

$$j_\nu = \kappa_\nu B_\nu(T_e), \quad (4)$$

where $B_\nu(T_e)$ is known as the Planck function. Thus, by taking into account that the radiation received by the telescope is, in fact, a compilation of the attenuated background radiation, the emissions and absorptions from the object that is being studied, and all of the material between the object and the telescope, we are left with an equation for the intensity received:

$$I_c(x) = I(0)e^{-\tau_c(0)} + \int_0^{\tau_\nu} \frac{j_\nu}{\kappa_\nu} e^{-(\tau_\nu - \tau'_\nu)} d\tau'_\nu. \quad (5)$$

This expression can be simplified by using the Rayleigh-Jeans formula: $\frac{j_\nu}{\kappa_\nu} = B_\nu(T_e) = \frac{2kT_e\nu^2}{c^2}$, if $h\nu \ll kT_e$. We then assume that the object that we are studying is homogeneous in density and temperature, and the foreground emission is zero. The integral from Eq (5) becomes much simpler, giving us

$$I(x) \approx \frac{2kT_e\nu^2}{c^2} (1 - e^{-\tau_c(0)}) \quad (6)$$

The radiative transfer of the free-free emission, neglecting the background sources, through the medium is

$$T(x) = T_e(1 - e^{-\tau_c(0)}). \quad (7)$$

Due to the frequency dependence of Eq (2), we must address how the extremities of our spectrum affect Eq (7). Lower frequencies in the HII regions cause κ , and thus τ_c , to become very large, $\tau_c \gg 1$. This results in blackbody emission. In order to compensate the temperature equation becomes $T(x) \approx T_e$. For high frequencies, we find that $T(x) \approx T_e\tau_c$, for $\tau_c < 1$. These deviations from Eq (5) were determined for the upper and lower bounds of the spectrum, not for its entirety. But free-free radiation is only part of what is found emanating from galaxies: synchrotron emission is also important. (Sources: Jonathan Baker "Free-Free (Bremsstrahlung) Radiation", Mark Gordon "HII Regions and Radio Recombination Lines" in Galactic and Extragalactic Radio Astronomy, and the University of Tubingen)

2.2. Nonthermal Radiation

When a particle is accelerated due to its interaction with a magnetic field, it travels in a spiral trajectory about the field lines. The circular path and the acceleration lead to polarized photon radiation, which takes on the shape of a cone when the velocity is relativistic, tangential to the orbit. Because this radiation mimics the type that is produced by a synchrotron particle accelerator, this is known as synchrotron radiation. Counter to bremsstrahlung radiation, synchrotron is nonthermal and it does not have the same peaked shape, but generally has a power law shape if the electron energy spectra is power law. It is one of the defining characteristics of supernovae remnants (SNR) in the radio spectrum.

In order for SNR to produce this type of radiation, one of two processes must occur. First, a magnetic field must be present. In which case, the only scenarios that seem plausible involve an existing field that is compressed and magnified by the shock wave from the SNR, amplification due to contact between ejecta and interstellar medium (ISM) as a result of the shock wave, or the presence of a nearby pulsar. Determining the actual history of the radiation requires specific observations that examine the geometry and profiles of each individual SNR. And, unfortunately, there are instances where the exact condition under which the magnetic field was produced is not understood.

The other possible circumstance for synchrotron radiation is when particles are moved relativistically in a magnetic field. For this to occur, a pulsar could be in the SNR, but this generation would only work for remnants with bright centers, or plerions. For shell-like structures, the acceleration would be due to the shock wave, or interactions between the moving particles and the disturbed, surrounding medium at the shock front. While it might seem that the collisions between the particles and the ISM would not favor any particular direction, reflecting off of each other in a random pattern, second-order Fermi acceleration results in a net acceleration forward.

2.3. Interferometry

As technology advances, we are able to view further and further into outer space at smaller angular dimensions. However, the instrumentation that we use may impede progress if it does not have the resolution suitable to the sources that are being observed. While it seems intuitive to build an enormous receiving surface, it is more economical monetarily and with regard to land, to synthesize an aperture. The power received from the source is given as

$$P = \frac{1}{2} \sum_{j=1}^N I_j^2 + \sum_{j=1}^{N-1} \sum_{k=j+1}^N I_j I_k \cos(\phi_j - \phi_k), \quad (8)$$

where j, k are the elemental areas that compose the aperture, N is number of individual areas, and $\phi_{j,k}$ is the relative phase of radiation. The first term is proportional to the sum of power at each j , while the cross-product defines how the power changes as the source moves, or the resolving power. Since P is measured as a summation of unit powers, only two mobile areas, j and k , measured in a sequential order, are actually needed to receive the full power. It is in this way that we are able to synthesize an aperture many times greater than could be built, and consequently, view

sources at a much higher resolution. The cross-product term in Eq (8) can be calculated after the actual observation using the data from the two elements.

Astronomers learned, as they experimented with aperture synthesis, that they could take advantage of the rotation of the Earth in order to maximize the area covered by their synthesized aperture. By placing the two antennas in the east-west direction, they were able to receive all possible radiation from the source in 12 hours. The addition of more arrays reduces the amount of time needed to transverse half of the globe. It also adds a new factor to the data. By separating the antennas at different distances from each other across the same latitude, the cross-product term of Eq (8) can be weighted according to the need of the observer or to more fully simulate a filled aperture.

In order to correlate the power recieved from the two antennas, which is the surface area used at the VLA, the time delay due to the distance between the antennas must be determined. When two antennas are a distance B apart, with the radiation's trajectory striking each antenna at angle θ (see Fig. 1), we connect the radiation's point of contact with antenna₂ to the trajectory of the radiation toward antenna₁ at a 90° angle. This then allows for a simple geometry where the time delay is given as $\tau = \frac{B}{c} \cos \theta$; the overhead position is at 0° . The voltage that is

FIG. 1.— The geometry of a two-element interferometer displaying the geometric time delay.

produced by the source at each antenna is given, where λ is the wavelength of the separation, as $V_1 \propto E \cos(\omega t)$ and $V_2 \propto E \cos[\omega(t - \tau)] = E \cos(\omega t - \frac{2\pi B}{\lambda} \cos \theta)$, with the corresponding time delay at antenna₂. These voltages are then sent through a multiplier and a low-pass filter, which results in the response

$$R(t) \propto S \cos\left(\frac{2\pi B}{\lambda} \cos \theta(t)\right). \quad (9)$$

The flux density, normally E^2 , is given as S here.

While Eq (9) is one of the fundamental equations in interferometry, it does not account for the adjustments that are made to the radiation waves before they enter the multiplier. The observed radio frequency (RF) must be amplified before anything else is done, so that the noise is filtered out of the signal. It is then combined with a monochromatic local oscillator (LO) with a coherent relationship, in other words, the LO must have a similar direction, amplitude, and phase. By combining the RF and LO through addition and subtraction, a heterodyne process, two new waves are created and called the intermediate frequency (IF). Once amplified, the IF is stripped of its high-frequency data. Then the data received from all of the antennas are multiplied and sent through a low-pass filter. All of the responses that are recieved from the antennas are modified with the appropriate time delay.

We defined Eq (8) as the power recieved at a filled aperture. However, synthesis incorporates other elements such as weighting (w_j), off-source radiation [σ , which is defined as $\sigma = (x, y)$ when using the u, v coordinate system], and the separations between the antennas (\mathbf{b}_j). All of these factors are designed to fill in the gaps that weren't covered by the antenna distribution, to more fully model a filled aperture. Putting all of this together,

$$P(x, y) = \sum_{j=1}^N \exp\{-i2\pi(ux + vy)\}w_j. \quad (10)$$

The other consideration that must be addressed is interference from the source, which is denoted as a complex number $V(u_j, v_j)$, the visibility function. By using an inverse Fourier transform, we are able to extract the brightness distribution source from V :

$$I(x, y) = \sum_{j=1}^N V(u_j, v_j) \exp\{-i2\pi(u_j x + v_j y)\}w_j. \quad (11)$$

This synthesis for the brightness of a point source can be done on an even $2^n \times 2^n$ grid, or a fast Fourier can be calculated - both techniques implemented by AIPS.

3. OBSERVATIONS

The Very Large Array (VLA), located on the plains of San Augustin in New Mexico, is made up of 27 radio telescopes configured in such a way that, while each antenna is 25m in diameter, the resolution is comparable to an antenna 18km in radius, $\sim .04$ arcseconds. It is as sensitive as a dish 65m in radius. By multiplying the data received from each telescope, the VLA works as an interferometer to create interference patterns from the data. A Fourier transform enables astronomers to take those patterns and glean information about the structure of the radio sources.

TABLE 1. 6CM HIGH RESOLUTION TABLE

Source	RA	DEC	Deconvolved Source Size			Peak Flux ^a	Total Flux
	(12^h56^m+) (s)	($21^\circ+$) (',")	Major	Minor	Pos ang	($\frac{mJy}{beam}$)	(mJy)
A.....	43.67	41 03.6	.272	.164	49.61	.612	.633
B.....	43.41	41 00.9	.379	.227	75.58	.874	1.17
C.....	43.43	40 58.9	.773	.540	128.3	.283	.266
D.....	43.64	40 59.1	.690	.467	107.2	.428	.510

^aThe 6cm map has a beam size of $.52' \times .51''$, position angle at -16° . Uncertainty is $.06 (\frac{mJy}{beam})$.

The antennas can be arranged in four formations, which are rotated about every four months: *A* array has a maximum of 36 km separating the antennas, *B* has a max of 10 km, *C* has 3.6 km, and finally *D* is separated as much as 1 km. There are also hybrid formations *DnC*, *CnB*, and *BnA*, that place the northern arms in the next larger arrangement than the SE and SW arms. Different receivers can be utilized in each of the radio telescopes in order to magnify the signal being recieved at a certain frequency or wavelength. The array can be sub-divided into as many as 5 sub-arrays, which can observe a different object at a different band simultaneously.

The data that we're receiving from the source resides in the UV plane. By performing an inverse Fourier series, we are able to reconstruct a map of sky. The quality of this map depends on the size of the (synthesized) aperture and the configuration of our baseline. While different configurations have the same total flux for a given source, they have different rms values, limiting the ability to see structure within an object. At the edge of the array, the radiation recieved from the source isn't as strong because the main beam cannot fully cover the source and thus the signal is weaker. However, this can be remedied by an additional weighting to the data. The bigger the telescope, the smaller the diffraction size since there is interference across the whole aperture - and thus, the more structure we are able to see. The beam size is roughly equal to the angular size of the source. To resolve the image, you need a smaller beam...but not too small. What we are ultimately trying to determine is the flux from the sources in the 2 cm and 6 cm.

Our data for NGC 4826 was taken in two epochs: older and newer sets of data, which were also of lower and higher resolution. The low resolution 6cm (4.89 MHz) data was taken in Sept-Oct 1982 in the B-configuration. The 2cm (14.96 MHz) data was received in the C-configuration in April 1983. Both sets of the high resolution data were in the A-configuration in March 1998. Absolute flux calibration was done using the quasar 3C 286. Phase center for all sets of data - once their epochs were matched to 2000, was at $\alpha = 12^h56^m43^s.55, \delta = 21^\circ40'60''$. In order to get the maximum visibility for the sources in NGC 4826, we combined both sets of the 2cm and the 6cm data. The 6cm, high resolution data with a taper of 600 and niter of 500 (Fig. 2, Table 1) was combined with the low resolution data that had a taper of 200 and niter of 500. The final map was not tapered, iterated, or reweighted. The 2cm, high resolution data had 400 taper and a niter of 50 and was combined with the low resolution, 170 taper, 50 niter data. The resulting map reweighted the high resolution data to .800, keeping the low resolution as the standard. The 6cm, low/high resolution map was convolved to the same beamsize as the final 2cm, low/high resolution map: $1''.32 \times 1''.27$.

4. OBSERVED RADIO PROPERTIES

Figure 3 shows the grey-scale image of the 6cm map with labels indicating the sources and their names in this frequency. Note that in Figure 4, the 2cm map, the sources are not identical. Some of the radiation that is present in one frequency, may not be present in another frequency. This, however, does not undermine the authenticity of a source in any way. By stating that the peak from a region must be above 3, or sometimes, 4 σ , we are assured that the flux is due to an actual source, and not just a product of aperature synthesis, Fourier transforms, etc.

In order to get a better understanding of the sources with respect to one another in each frequency, Figure 5 is a contour plot with the 2cm low/high resolution data overlayed on the 6cm low/high resolution. While sources A-D appear to remain stationary across both frequencies, source E is only seen in the 6cm map. Intuitively, it would seem as if the source "moved" to the right in the 2cm map, however, the maximum that a source could move and still be the same source is roughly one beam size. Thus, we concluded that F was an entirely different source. Source G only showed up in the 2cm map.

The most interesting source was H. In the 2cm map, the source was obviously bright and proved to be a real source. However, all of the radiation, including background, at that location was completely blocked in the 6cm frequency. Table 2 gives the position, size, peak flux, total flux, and spectral indices for both fluxes of each source. The peak flux that is listed for source H in the 6cm map is actually an upper limit, due to the fact that no radiation is apparent.

Spectral indices divulge right away the type of radiation that is present at a source. If they are defined as $S_\nu \propto \nu^\alpha$, then $\alpha > -0.1$, a positive index, represents thermal emission. Synchrotron emission go as $\alpha < -0.1$. Source H was the only source whose spectral indice for the peak flux was positive. Thus, it was the only source with free-free emission.

In an H_2 region at equilibrium, the ionization rate is equal to the recombination rate, and both of these are collisional processes. The free-free emission is also a collisional process. Thus, we are able to say that flux from a thermal region is proportional to the ionizing photons emitted from that region. Based on the amount of ionization, and the initial mass function of a galaxy, it is possible to estimate the number of O stars and supernovae remnants that are currently

TABLE 2. INDIVIDUAL RADIO SOURCES IN NGC4826

Source	Map	RA	DEC	Deconvolved Source Size			Peak Flux ^a	Total Flux ^b	α_p ^c	α_t ^c
		($12^h 56^m +$) (s)	($21^\circ +$) (', '')	Major	Minor	Pos ang	($\frac{mJy}{beam}$)	(mJy)		
A.....	6cm	43.66	41 03.6	2.68	2.12	126	01.2	01.9	-0.8	-1.3
	2cm	43.69	41 03.4	1.46	.196	117	0.52	0.45		
B.....	6cm	43.41	41 00.8	2.18	1.78	147	01.7	02.0	-0.9	-1.1
	2cm	43.42	41 00.6	2.36	.671	146	0.62	0.62		
C.....	6cm	43.44	40 59.3	3.05	2.45	007	01.1	01.1	-0.6	-0.4
	2cm	43.43	40 58.5	2.68	1.94	046	0.55	0.73		
D.....	6cm	43.64	40 59.1	3.06	2.67	172	01.3	01.9	-0.6	-1.0
	2cm	43.63	40 59.4	2.54	1.50	165	0.67	0.60		
E.....	6cm	43.78	41 00.6	2.99	2.69	138	01.1	01.3	...	...
	2cm	...	...	...	...	...	< .3	...		
F.....	6cm	...	...	...	...	...	< .2	...	...	...
	2cm	43.66	41 00.4	4.25	1.03	084	0.62	0.65		
G.....	6cm	...	...	...	...	...	< .2	...	...	...
	2cm	43.94	40 59.8	1.76	.923	173	0.49	0.45		
H.....	6cm	43.01	40 54.9	...	...	...	0.24 ^d	01.2	.6	-.8
	2cm	42.97	40 55.2	2.11	.942	073	0.50	0.50		

^aPeak flux is determined for maps with a beam of $1''.32 \times 1.27''$, and a position angle of -68° . Uncertainty goes as the rms, which is $.06 (\frac{mJy}{beam})$ for the 6cm map and $.11 (\frac{mJy}{beam})$ for the 2cm map.

^bThe 6cm map has an uncertainty in the total flux between 3–5% for all sources except H, which is $\sim 10\%$. The 2cm map has uncertainties good to 17–22% for all sources but G, which has $\sim 25\%$ uncertainty.

^cThe spectral index takes into account the ratio of the 2cm and the 6cm flux - meaning it is not specific to the 6cm row. Uncertainty for α_p is $-.3, +.5$ and α_t is $-.4, +.6$.

^dSince source H in the 6cm is actually a hole, the peak flux is actually the upper limit of the flux in that region. Mean Flux = $.327$ mJy, Max = $.468$ mJy/bm, Min = $.201$ mJy/bm.

visible. From Turner and Ho (ApJ, 1994), the Lyman continuum rate gives the ionization

$$N_{Ly\alpha} = 1.1 \times 10^{50} s^{-1} \left(\frac{S_{2cm}}{mJy} \right) \left(\frac{D}{Mpc} \right)^{-2} \quad (12)$$

For source H, with respect to only O and B type stars, $N_{Ly\alpha} = 1.4 \times 10^{-51} s^{-1}$. Thus, we are looking at approximately 140 O stars. More accurate than the Lyman continuum rate for estimating the number of stars, is the luminosity - since it comes mostly from O and B type stars in any cluster. But $N_{Ly\alpha}$ is a good measure the luminosity: $L_{OB} = 7.4 \times 10^7 L_\odot$. Based on the lifetime of O stars, the period for which they are visible as supernovae, and the amount of SNR that we expect to see in a galaxy of this sort, we found that there was actually a burst of activity that has caused an unusually large amount of star formation in the center of NGC 4826. This activity may be due to an outflow from the center, shock excitation from SNR, possibly an active galactic nuclei - we are not sure. And unfortunately, there is a lot of extinction in the optical wavelengths, so we cannot look direction at the star formation embedded within. However, our results are very intriguing and will require more data to be more conclusive.

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