LOW FREQUENCY CUTOFFS IN THE SPECTRA OF RADIOQUIET QUASARS

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ABSTRACT. Radio-quiet and normal radio-loud quasars have very similar spectral properties in the ultraviolet, optical and near infrared regions, but their radio powers differ by several orders of magnitude. Somewhere between the near infrared and the radio their spectra must diverge dramatically.

The IRAS survey detected 17 radio quiet quasars and luminous Seyfert 1's with $-29.5 < M_V < -21.6$ (for $H_o = 75$). By coadding the survey data and using pointed observations, we have detections of most of these objects in all four IRAS passbands. The spectra are all rising with wavelength all the way to 100μ. We are measuring fluxes in the centimeter, millimeter, and, together with R Cutri, the near infrared and optical regions for each of these objects. Our goal is to constrain the location, shape, and spectral context of the low frequency cutoffs. Here we present the IRAS, millimeter and centimeter data. Measurements at the other wavelengths are still in progress.

Although the spectra are rising steeply between 60μ and 100μ, we find that all of our objects are undetectable at 1.3 mm with the NRAO 12-m telescope. Our limits are typically an order of magnitude below the 100μ fluxes. (Ennis et al (1982) and Robson et al (1985) have already shown that the 1 mm fluxes of some radio quiet quasars must be below the extrapolation of the near infrared continuum.) Our objects are all extremely weak or undetected with the VLA at 2 cm and 1.3 cm, at levels typically three orders of magnitude below the 100μ fluxes. The sharpness of the required cutoffs allows us to rule out the hypothesis that the infrared is synchrotron radiation with the cutoff due to an absence of low energy electrons. The high frequency of the cutoffs makes free-free absorption implausible, but not impossible. It is possible that synchrotron self-absorption is suppressing the radio. There is circumstantial evidence that the far infrared is thermal dust emission. This would require a lower cutoff in the distribution of dust temperatures, which we think we can explain.

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I. INFERENCES FOR THE SYNCHROTRON MODEL

Condon et al (1981) point out that if the difference between radio quiet and radio loud quasars is just the synchotron self absorption turnover frequency then the former objects are much smaller than the latter ones. This isn't reflected in optical variability timescales. If we arbitrarily assume a brightness temperature of 10^{12}K, the radius of a typical source, PG 0906+484, would be a tiny $\sim 2\times 10^{-4}$pc for $H_o = 100$. We use $H_o = 100$ here so that we can compare with Band and Grindley (1986), who model two of our objects with sychrotron self Compton sources. For PG 0906+484, they find a much lower brightness temperature of $\sim 10^9$K, corresponding to a source size $\sim 6\times 10^{-3}$pc. In these comparisons, we've taken a turn-over wavelength of 100μ and no "thermal source." In the Band and Grindley models, the magnetic energy densities exceed the particle and photon energy densities by orders of magnitude.

One possible key to testing the synchrotron self absorption hypothesis is a study of the spectra of the cores of lobe dominant quasars. For these objects there is no evidence for the core radio emission being beamed from a jet; it is probably just self-absorbed synchrotron radiation from the stationary core. If the radio spectra rose or at least stayed flat with frequency in the centimeter-millimeter region, and joined with the infrared, then the infrared would perhaps also be synchrotron radiation from the same component. In fact we know this isn't generally the case because Rudnick et al (1986) have shown that the self-absorbed radio cores usually turn over (become optically thin) in the centimeter range. The spectra apparently reach deep minima in the millimeter range before rising up to the infrared. If the infrared were due to self-absorbed synchrotron radiation there would be two such sources superimposed in the nuclei, with no continuity between them. If the infrared isn't self-absorbed synchrotron radiation in these cases, it probably isn't for the radio quiet quasars either, since the two groups have similar optical/infrared properties.

II. CAN FREE-FREE ABSORPTION SUPPRESS THE RADIO EMISSION?

Condon et al (1981) suggest free-free absorption as a possible cause of the lack of radio emission. The high frequencies we find for the turnovers make this difficult. A slab of ionized gas with a density of 10^9 cm^{-3} and a thickness of 10^{12} cm will have significant optical depth at 1mm. The same slab thickness will absorb at 100μ if the density is 10^{10} cm^{-3}. These densities and thicknesses are similar to those in broad line emitting clouds, but those clouds are optically thick in the Lyman continuum. The problem with that is we know observationally that most quasars can be seen shortward of 912Å, so that the broad line cloud covering factors must be low.

Because of this problem, Condon et al suggested that the free-free absorbers are related to the broad line clouds, but shallower and optically thin in the Lyman continuum. The clouds do need to be opaque to free-free absorption in the submillimeter region, requiring the emission measure $N_e^2 l$ to be at least 10^{31} cm^{-5}. At the densities and ionization parameters typical of broad line clouds such an emission measure must be accompanied by a high Lyman continuum optical depth (Kwan and Krolik 1981 - Fig. 2). But free-free absorption is still possible if the absorbing clouds have a very high ionization parameter! If the spectral cutoff can be shown to be extremely steep, free-free absorption will be indicated. This possibility cannot be excluded on the basis of X ray absorption limits, because free-free depends on emission measure, not column density.

III. THERMAL COMPTONIZATION

Suppose we could think of a source of soft "seed" photons at $\sim 10^{12}$HZ. If these photons were inverse-Compton scattered by a hot gas, e.g. the hot intercloud medium invoked to confine the broad emission line clouds, a power law spectrum could be produced all the way up to $\sim m_e c^2$. Of course the low energy cut- offs, which we seek to understand, would just be attributed to the low energy cutoffs of the seed spectra.

Ennis et al (1982) show in the Figure 3 the region of Compton optical depth τ and electron temperature T_e parameter space suited to the hot intercloud medium. Observationally, we know that for $T_e \sim 10^7$K the optical depths must be $\tau \lesssim 0.5$; otherwise emission lines would generally show strong electron-scattering wings. Actually we believe the optical depths are probably less than one even if the hot intercloud media are too hot to produce visible line wings, because otherwise the intrinsic emission line to continuum ratios would be implausibly high. Furthermore we know that the far infrared continua typically have spectral indices of ~ -1, so there is essentially no Comptonization solution possible, according to the Ennis et al figure.

Another objection to this idea is that the power law spectral index predicted is very sensitive to both T_e and τ (see Pozdnyakov et al 1979 for the optically thin calculation). The narrow range in observed spectral indices would be hard to explain.

IV. DUST EMISSION IN THE FAR INFRARED?

In the 12μ - 100μ region our spectra are fairly smooth, and the spectral shapes don't strongly suggest thermal emission from dust. However, dust from a wide range of temperatures could produce the observed spectra (e.g. Rees et al 1969). Furthermore, steep spectral cutoffs between 100μ and 1 mm are characteristic of many extragalactic sources for which the spectral shapes do suggest dust, e.g. Arp 220, NGC 1068 and NGC 253 (Joy et al 1986; Hildebrand et al, 1977). Here we consider whether the far infrared sources in our quasars are analogous to those in the dust-emission galaxies.

In the dust sources the spectra rise rapidly with wavelength in the infrared because the dust mass increases rapidly with decreasing temperature. The spectral cutoffs in the submillimeter region show that this is no longer true below ~20 - 40K. If the dust clouds are heated only by optical and ultraviolet light, one would expect increasing amounts of dust down to very low temperatures. However, there is a heating source which can penetrate the cooler dust and perhaps establish a lower limit to the dust temperature in the nuclear regions: the far infrared dust radiation itself.

We suggest that the emitting regions of IRAS galaxies are probably very small and of significant optical depth, based on the fact that Sc galaxies detected at 100μ are known to be preferentially face on (see the data of Burstein and Lebofsky 1986). This interpretation of the aspect effect is supported by the results of Joy et al (1986) who show directly that the 100μ emitting region of Arp 220 has r<1.5 kpc and so $\tau>0.05$. A 100μ luminosity of 10^{12} $L_{\odot}$, T=45K and optical depth of order unity or higher implies a 100μ source radius ~300pc. Dust at the edge of such a 10^{12} $L_{\odot}$ far infrared source can get no cooler than ~40K, perhaps explaining the low frequency spectral cutoffs. For some galaxies, e.g. NGC 1068, we also know that the sources are optically thin in the 300μ -1mm region because their spectra are steeper than the Rayleigh-Jeans spectrum there. This situation would have to be modeled, including the effects of dust in the disks of the host galaxies, to see whether or not our explanation of the apparent minimum in dust temperature is correct.

Significant optical depths in the far IR imply high optical depths in the middle and near IR, perhaps explaining why AGN spectra do not generally show dust features in those regions. (See the data of Aitken and Roche 1985). On the other hand IRAS galaxies do show features, suggesting that this reasoning is invalid so that the primary nuclear continuum does dominate quasar spectra in the middle and near IR.

We can estimate the minimum dust masses required by assuming a value of the mass absorption coefficient at the turnover frequencies. Assuming a ν^2 emissivity law, the 100μ and 60μ fluxes from PG 0906+484 imply a dust temperature of 31K. The Hildebrand et al formula gives 20 cm^2/gm for the mass absorption coefficient at 100μ, but they point out that the coefficient is also subject to an upper limit of ~10 cm^2/gm. This value leads to a dust mass of $\sim 10^8$ $M_{\odot}$. For our most luminous object, PG 1634+706, $M_V \sim -30$ and $\sim 10^9 M_{\odot}$ of ~88K dust would be required.

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