Emission-Line Probes of Circumnuclear Dust in AGNs

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Abstract. Emission lines that trace elements subject to strong depletion onto grains provide a means for probing the dust content of AGNs. Examples include infrared [Fe\textsc{ii}] and optical [Ca\textsc{ii}] lines. The excitation mechanisms underlying the [Fe\textsc{ii}] lines remain controversial, resulting in related disagreement over the gas-phase abundance of iron in Seyfert narrow-line regions. In this contribution we emphasize the utility of the [Ca\textsc{ii}] features as a consistency test for claims of grain destruction affecting the [Fe\textsc{ii}] lines. A search for [Ca\textsc{ii}] emission in NGC 1068 at the location of strongest [Fe\textsc{ii}] emission along the radio jet yields a strong upper limit, but no detection. This result suggests that grains survive largely intact in a region that otherwise shows strong evidence of shock processing.

1. Introduction

Dust in the circumnuclear environment can be important for modifying our view of the narrow- and broad-line regions in AGNs. Netzer & Laor (1993) have suggested further that dust in the emission-line regions has a major role in establishing the NLR/BLR dichotomy. Dust is also clearly implicated in reprocessing a significant part of the continuum luminosity generated on small scales, with resultant emission appearing at infrared wavelengths. A detailed knowledge of dust properties in AGNs is thus desirable, but our understanding of grains in these environments remains primitive.

Emission-line diagnostics provide one means of probing the dust content of the NLR. The basic strategy is to measure nebular line fluxes from elements subject to depletion from the gas phase; if these features do not play a dominant role in cooling the plasma, their strength can be expected to scale approximately in proportion to the gas-phase abundance of the responsible element (see, e.g., Kingdon et al. 1995 and references therein). The degree of depletion can then be used to infer the prevalence of grains incorporating this element.
2. Infrared [Fe II]

In the local interstellar medium, the gas phase fraction of iron is $\sim 10^{-2}$ (Savage & Sembach 1996), making this element a potentially useful tracer of grains. Iron is commonly detectable in Seyfert galaxies through prominent narrow-line emission in [Fe II] 1.257 $\mu$m, 1.644 $\mu$m. The understanding of these lines and their observed strengths remains controversial, however, with different researchers arguing for excitation via supernovae (Greenhouse et al. 1991), other forms of shocks (e.g., Veilleux et al. 1997), or photoionization (e.g., Mouri et al. 1993; Simpson et al. 1996). The disagreement over excitation leads to a related divergence of opinion on gas-phase abundance, with some authors claiming that strong [Fe II] emission implicates substantial grain destruction, presumably in shocks.

While the energetics of Seyfert NLRs are probably not globally dominated by shocks (e.g., Laor 1998), there are nonetheless good reasons to take shocks seriously in conjunction with the observed [Fe II] emission. First, there is a strong statistical correlation between [Fe II] and radio continuum emission in Seyfert nuclei. While at first glance this trend might be dismissed as an illustration that more powerful galaxies radiate more at all wavelengths, Veilleux et al. (1997) point out that the [Fe II]/radio correlation is considerably stronger than correlations between [Fe II] and X-ray luminosities, even when hard X-rays (which are less susceptible to absorption) are considered. If [Fe II] emission is powered primarily by photoionization, a robust correlation between the line and ionizing continuum luminosities might be expected; the fact that the [Fe II]/radio correlation appears stronger may implicate a significant role for mechanical heating of the nebula (as traced by [Fe II]) by the radio plasma.

A second suggestion that shocks driven by radio plasma may be important in generating [Fe II] emission is seen in a spatial correlation between these two emission components in NGC 1068, one of the best-studied sources in terms of spatial resolution. Blietz et al. (1994) have published a comparison of [Fe II] 1.644 $\mu$m emission and 5 GHz radio maps, which shows that the [Fe II] emission is concentrated around the inner part of the extended radio structure, in a region that might be expected to contain material that was shocked in the earlier passage of the expanding jet. While alternatives to shocks (e.g. photoionization by radiation collimated parallel to the jet) can be invoked to account for the nebular gas, the correspondence between the radio and [Fe II] morphologies is nonetheless suggestive.

Finally, Veilleux et al. (1997) report that Seyfert 2 nuclei exhibit [Fe II] 1.257 $\mu$m emission line widths that are often broader than widths for hydrogen recombination lines. The larger widths for the low ionization [Fe II] lines may indicate that this emission traces a kinematically disturbed component of gas in the NLR, consistent with a connection to shocks.

3. Optical [Ca II]

An independent test of grain destruction in the NLR is provided by measurements of [Ca II] $\lambda\lambda$7291, 7324 (Ferland 1993). Calcium tends to be highly depleted onto grains in the normal ISM, with a typical gas-phase fraction of only
\[ \sim 10^{-3} \] Power-law photoionization models appropriate for the NLR that assume solar abundances in the gas phase predict strong emission in the [Ca\textsc{ii}] lines, at a level comparable to or exceeding that in the more familiar red lines of [O\textsc{i}], [S\textsc{ii}], and [O\textsc{ii}] \( \lambda\lambda 7290, 7331 \).

The absence of significant [Ca\textsc{ii}] emission in the spectra of Seyfert nuclei has been interpreted as evidence that the NLR hosts a largely intact population of grains (Ferland 1993), with the corollary that grain destruction in shocks is unimportant in these environments, at least in some global sense. An important consistency test comes from observations of [Ca\textsc{ii}] in plasmas that are known to be shocked. Spectra of supernova remnants (e.g., Vancura et al. 1992) and outflows from Herbig-Haro objects (e.g., Morse et al. 1996) show significant emission in the [Ca\textsc{ii}] lines, validating the use of these features as probes of grain destruction.

While shocks may be unimportant in the global energetics of the narrow-line region, there are strong indications that shocks are important in localized portions of the NLR. The evidence comes from apparent shock structures that are either resolved in optical imaging (e.g., Capetti et al. 1997) or inferred from kinematic correlations with radio properties (Whittle et al. 1988). These sites may additionally play an important role in generating [Fe\textsc{ii}] emission seen in the global spectra of the Seyfert NLRs. A search for [Ca\textsc{ii}] emission in these localized sites would provide a useful constraint on the significance of shocks in these regions, while also directly probing the degree of grain destruction.

4. A Test Case: NGC 1068

The prototypical Seyfert 2 galaxy NGC 1068 provides a useful testbed for assessing the role of shocks within the NLR and the resulting consequences for [Fe\textsc{ii}] and [Ca\textsc{ii}] emission. The nucleus of this galaxy features a radio jet with a well defined bow-shock structure (e.g., Wilson & Ulvestad 1983), and correlated nebular emission (Capetti et al. 1997). The optical emission features exhibit line-splitting of up to 1500 km s\(^{-1}\), interpreted as a signature of gas motions driven by the expanding synchrotron plasma (Axon et al. 1998). As noted previously (§2), the correspondence between the radio and [Fe\textsc{ii}] emission structures provides circumstantial evidence favoring a role for shocks in generating the [Fe\textsc{ii}] luminosity.

In order to test this scenario further, we have conducted a search for [Ca\textsc{ii}] emission in the extended NLR in the environs of the detected radio and [Fe\textsc{ii}] emission. The data used for this purpose were acquired in a one-hour exposure with the Canada-France-Hawaii 3.6-m telescope in conjunction with the MOS/ARGUS integral field optical fiber spectrometer. The optical fibers project to a diameter of 0.4\(''\), and the resulting data have a spectral resolution of \(\sim 5\)A.

A spectrum corresponding to a 1.6\(''\) \(\times\) 1.1\(''\) aperture centered on the peak of the [Fe\textsc{ii}] emission (northeast of the nucleus) is shown in Figure 1. The expected location of [Ca\textsc{ii}] \(\lambda 7291\) emission is indicated by the vertical bar. [Ca\textsc{ii}] \(\lambda 7324\), if present, is blended with [O\textsc{i}], but the \(\lambda 7291\) feature is expected to be the stronger line of the [Ca\textsc{ii}] doublet, with a theoretical intensity ratio of \(I(\lambda 7291)/I(\lambda(7324) \approx 3\).
Figure 1. Spectrum of NLR emission in NGC 1068, with the expected location of [Ca\textsc{ii}] λ7291 indicated.

No [Ca\textsc{ii}] emission is apparent in the spectrum in Figure 1, and inspection of other spectra from this data set for nearby regions in the extended NLR of NGC 1068 similarly yield a negative result. A useful way of expressing this finding is as a 3-σ upper limit of $I([\text{Ca\textsc{ii}}]λ7291)/I([\text{O\textsc{i}}]λ6300) < 0.05$. For comparison, supernova remnants in the published literature commonly show values for this ratio of $\sim 0.2 - 0.3$. The lack of [Ca\textsc{ii}] in the purportedly shocked regions of NGC 1068 thus presents a puzzle; if the gas has been shocked it appears that the grains have largely survived intact. This result then argues against grain destruction as an important factor in the generation of strong [Fe\textsc{ii}] emission in this source.

While the missing [Ca\textsc{ii}] could be invoked as evidence against the presence of shocks in the NLR, it may be possible to turn this argument around and use the survival of grains as an interesting constraint on the shock physics that is operative in these environments. As an example, theoretical studies of dust processing in shocks indicate that the amount of grain destruction is strongly influenced by sputtering following betatron acceleration as the grain traverses the shock (Jones et al. 1994). The amount of gas compression and resulting acceleration is influenced by the magnetic field; stronger $\vec{B}$ fields parallel to the shock front will contribute magnetic pressure that reduces the amount of compression in the shock. The survival of grains in the NLR may thus lead to useful constraints on the magnetic field in these environments.
5. Conclusion

Emission lines can be used to place useful constraints on the grain population in Seyfert NLRs. Features of \([\text{Fe} \, \text{II}]\) and \([\text{Ca} \, \text{II}]\) are of particular interest in this regard, and one point we wish to emphasize in this contribution is that these two emission tracers are best analyzed in parallel; more specifically, judgements regarding the role of grain destruction in enhancing \([\text{Fe} \, \text{II}]\) emission should also take into account the constraints provided by \([\text{Ca} \, \text{II}]\) measurements or limits.

While the \([\text{Ca} \, \text{II}]\) lines are globally weak in Seyfert nuclei, these features might be detectable in localized nebular regions where independent evidence exists for shocks driven by radio plasmas. Our initial pilot study of NGC 1068 has produced a null result, however. This rather surprising outcome may be employed to place interesting constraints on the nature of shocks that do, in fact, occur within Seyfert galaxies.

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Discussion

Martin Gaskell: Of course it’s been known for a long time from emission-line reddening indicators that there is substantial internal reddening in NLRs \((E(B − V) \sim 0.5)\).

Ray Norris: So where do you think the \([\text{Fe} \, \text{II}]\) is coming from in NGC 1068?

Joe Shields: I suspect that it’s largely a product of a normal, photoionized, and dusty, NLR; the same conclusion was drawn on more quantitative grounds by Simpson et al. (1996), who compared measured line strengths with predictions of a simple \(\text{Fe} \, \text{II}\) model atom. In the near term it should be possible to test this idea more rigorously, as sophisticated \(\text{Fe} \, \text{II}\) models are incorporated into photoionization codes.