H_2 Emission from External Galaxies

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ABSTRACT. 2 μm spectroscopic observations by many authors have revealed significant rotation-vibrational H_2 emission is widespread from starburst to bare nucleus galaxies. Near-IR H_2 emission lines can arise from various excitation sources: UV radiation by hot stars, shock excitation by supernova remnants or AGN driven winds, and UV/X-ray radiation by an AGN. In this review recent data will be compared with such H_2 excitation models.

1. H_2 line ratio; Is H_2 emission is thermal?

Rotation/vibrational H_2 emission around 2μm has been observed in all types of emission line galaxies from HII region galaxies to bare nucleus objects (e.g., Kawara, Nishida, and Gregory 1987 & 1990; Fisher et al. 1987; Moorwood and Oliva 1988). There are three plausible H_2 sources to excite H_2 gas; shocks, far-UV radiation and X-ray radiation. The shock excitation thermalizes the level population at temperatures of ~ 2000 K, resulting in the line ratio of 2-1S(1)/1-0S(1) ~ 0.1. In the H_2 excitation due to far-UV radiation (912 - 1108 Å), radiative fluorescent H_2 emission is produced in cold gas with density below ~ 10^4 cm^{-3} where relative line intensities are characterized by the non-thermal population, such as 2-1S(1)/1-0S(1) ~ 0.5, while thermal H_2 emission is produced in warm (T > 1000 K) dense gas heated by intense UV radiation (Sternberg and Dalgarno 1989). In the H_2 excitation due to X-ray radiation modeled by Lepp and McCray (1983), H_2 emission can also consist of the thermal and non-thermal components. Thermal H_2 emission is produced in warm clouds near a X-ray source, while non-thermal H_2 emission is produced in cool clouds by non-thermal electrons. The non-thermal component becomes significant and the ratio of the thermal to non-thermal component is 0.25 in the 1-0S(1) line for clouds with column densities of 10^{24} cm^{-3} located near the X-ray source.

In the sample galaxies exhibiting Seyfert and/or starburst activity taken by Moorwood and Oliva (1990), the data [2-1S(1)/1-0S(1) vs 1-0S(0)/1-0S(1)] falls between the Orion cloud (pure shock excitation) and the prediction by the pure UV fluorescent excitation (or pure non-thermal excitation). This suggests that extragalactic H_2 emission is a mixture of thermal and non-thermal components.

Another example is the spectrum of NGC 6240 taken by Lester, Harvey, and Carr (1988), although this remarkable interacting/merging galaxy is not a

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typical example. Analyzing this spectrum, Tanaka, Hasegawa, and Gatley (1991) demonstrated that H_2 emission in NGC 6240 consists of the thermal and non-thermal components; 70% of 1-0S(1) originates from gas thermalized at 1600 K, and 70% of the total H_2 luminosity is non-thermal. They suggested UV radiation by B stars as the major source for the excitation. Drain and Wood (1990) also decomposed the H_2 emission lines, and found the similar contribution from the thermal and non-thermal contribution. They explained the results in terms of X-ray radiation as the source of the thermal component and of UV radiation as that of the non-thermal component. It should be noted that 1-0S(1)/3.28μm is 10 times greater in NGC 6240 than in other starburst galaxies (Mouri et al. 1990a). This suggests that the observed 1-0S(1) intensity has an excess of 10 over the predicted value from the UV radiation in NGC 6240, since the 3.28μm dust emission is powered by the similar UV photons as used for H_2 emission.

2. Comparison with other emission lines

The 1-0S(1) line luminosity relative to the far-infrared luminosity is enhanced in AGNs than in starburst galaxies (Kawara, Nishida, and Gregory 1987 & 1990). Finding the linear correlation between the 1-0S(1)/Brγ and [OI]6300/Hα, Mouri et al. (1989) demonstrated that 1-0S(1)/Brγ is a powerful tool to distinguish between AGN and starburst galaxies as in the case of [OI]6300; 1-0S(1)/Brγ is clearly greater in AGNs than in starburst galaxies. The linear correlation suggests H_2- and [OI]-emitting regions are closely related to each other. The ionization potential of O^0 (13.62 eV) exactly matches that of H^0 (13.60 eV), and so [OI]-emitting regions must be located outside fully ionized regions. It is generally considered the [OI] emitting region is due to electron collisions in the partly ionized regions. In the case of AGNs, extended partly ionized regions are formed by intense X-ray radiation from the central source. In starburst galaxies, the [OI] emission comes from the narrow transition zone at the boundary of the Stromgen sphere (e.g., Veilleux and Osterbrock 1987) or from shock-heated gas (Cambell 1988) probably associated with supernova remnants. This linear correlation thus favors X-ray excitation in AGNs and shock excitation in starburst galaxies. However, Mouri and Taniguchi (1991) recently found that 1-0S(1)/Brγ of starburst galaxies can also be explained by UV florescent models only if [OI]6300 is powered by supernova remnants.

Comparison with [FeII]1.644μm is also of great interest, because [FeII]/Brγ is greater in AGNs than in starburst galaxies, being linearly correlated with 1-0S(1) (Kawara, Nishida, and Taniguchi 1988; Moorwood and Oliva 1988; Mouri et al. 1990b). In starburst galaxies, the [FeII]1.644μm emission is probably powered by shocks associated with supernova remnants (Joseph et al. 1987). Recently, the [FeII]1.644μm and 1-0S(1) lines were detected by Graham, Wright, and Longmore (1990) in the Crab nebula where a UV-X-ray power-low continuum excites line emission. They concluded, "Given the many similarity between the NLR (narrow line region) in NGC 4151 and the Crab Nebula filaments, ... the IR [FeII] 1.644μm emission from NGC 4151 can be entirely accounted for by the standard NLR model. There is no evidence for any excess [FeII] 1.644μm emission and no need to invoke shocks, either from supernova remnants or from galactic winds."

Hence if a single excitation mechanism controls [OI]6300, [FeII]1.644, and 1-0 S(1), H_2 emission in AGNs results from X-ray radiation and that in starburst galaxies is excited through shocks by supernova remnants. However, it is more likely that UV radiation by young stars and shocks by supernova remnants share H_2 emission in starburst galaxies because the H_2 emission appears to be a combination of the thermal and non-thermal components.

3 H_2 excitation source in AGNs

Detecting broad emission lines in polarized light from NGC 1068 (type 2 Seyfert), Antonucci and Miller (1985) hypothesized that the molecular torus completely hides the inner BLR (broad line region) from our view. The classification of Seyfert types is determined by the angle of the line of sight relative to the torus: type 2 Seyferts for the edge-on view and type 1 Seyferts for the face-on view. Recent X-ray observations by the Ginga satellite are finding X-ray emission from type 2 Seyferts and LINERs (e.g., Koyama 1989). It is natural to consider that all AGNs are X-ray sources which are surrounded by molecular clouds. In fact, the H_2 1-0S(1) was detected in NGC 4151 (Fisher et al. 1987) and NGC 3783 (Kawara, Nishida and Gregory 1989) which are classified into bare nucleus objects that has no excess emission in the far-infrared and no reddening in the optical. In the torus model developed by Krolik and Lepp (1989), dense clouds located near the central source (torus's inner edge is ~ 1 pc from the central source) are heated up to ~ 1,000 K by hard X-ray radiation. Hence, H_2 spacial distribution of type 1 Seyferts would have a point source at the center surrounded by a diffuse extended envelope which is caused by the heating of circumnuclear clouds. In type 2 Seyferts, we would not see a bouble-peaked H_2 emission because the inner part of the torus is obscured by outer clouds. Although there is a correlation between 1-0S(1) and X-ray (2-10Kev) intensities (Kawara, Nishida, and Gregory 1990), it is not clear that the observed H_2 emission in type 1 Seyferts is dominated by the X-ray powered H_2 emission, because the H_2 luminosity of the type 2 Seyfert NGC 1068 is comparable to those of type 1 Seyferts.

Rotaciuc et al. (1991) published the extended H_2 emission in a type 2 Seyfert NGC 1068. The H_2 emission is more extended than the Brγ region. The H_2 emission is minimized at the compact 2 μm continuum source with two unequal emission peaks ~ 1.3" (100 pc) on either side. The lowest contours extended about 4" (300 pc) from the compact continuum source. We should keep in mind that 2-1S(1)/1-0S(1) is ≤ 0.14 in a 6"x6" slit, thus the H_2 emission is dominated by the thermal component (Moorwood and Oliva 1990). The H_2 emission appears to be a torus-like structure at the center of which the 5GHz jet start to outflow 30° away from the pole of the molecular torus. The radio jet appears to be interacting with the molecular torus just above the major H_2 peak. If this is the case, the gas outflow from the center would be responsible for the extended H_2 emission. Observing [NII]6548, 6583 and using a mass outflow rate of ~ 0.4 M⊙ yr^{-1} predicted by Krolik and Begelman 1986, Cecil, Bland, and Tully (1991) estimate ~ 10^{44}

ergs s^{-1} for the wind kinetic luminosity, which is much greater than $3x10^{41}$ ergs s^{-1} that is required to be dissipated to produce the observed H_2 1-0 S(1) luminosity (Rotaciuc 1991). The UV to X-ray continuum is another obvious source for the H_2 excitation. In fact, Rotaciuc et al. (1991) discussed that the observed surface brightness of the H_2 emission is consistent with that in the photodissociation model with gas densities ≥ 5 x 10^5 cm^{-3} (Sternberg and Dalgarno 1989), in which case the level population is thermalized. The X-ray luminosity (2-10KeV) of NGC 1068 is possibly ~ 10^{44} ergs s^{-1} (Koyama 1989), which can produce the 1-0S(1) H_2 luminosity of ~ 10^{41} ergs s^{-1} if the X-ray source is spherically surrounded by molecular clouds (Lepp and McCray 1983). This value is also consistent with the observed 1-0S(1) luminosity 7 x 10^{39} ergs s^{-1}. If this is the case and if the column density of clouds is 10^{23} cm^{-2}, the non-thermal component contributes only 10% of the observed 1-0S(1) luminosity, resulting in 2-1S(1)/1-0S(1) = 0.06 (Lepp and McCray 1983).

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QUESTIONS AND ANSWERS

C.Henkel: What additional insight in the pumping mechanism can be gained by measuring higher excited H_2 lines?

K.Kawara: I am not a right person to answer this question. What I can say is that in the UV-pumping, for example, pumped levels cascade down to lower level, resulting in more chances to emit higher level emission than in the thermal process. So, the higher level lines can provide a diagnostics to determine the dominant excitation mechanism.

A.Sternberg: It is unlikely that the H_2 emission in Seyfert 1's are produced in an observing torus of 1 pc size since the luminosities of Sy 1's and Sy 2's are comparable and in Sy 2's the H_2 emission is extended over $\sim$ 100 pc scales.

K.Kawara: I agree with your argument. However, it seems to me that the torus model is one of plausible models to explain the double-peaked H_2 map of NGC 1068 and the more enhanced H_2 emission in Sy 1's than in Sy 2's. Otherwise, we have to figure out an alternative cloud configuration which can minimize the H_2 emission at the galactic center of NGC 1068. The best estimate of the x-ray luminosity (2 - 10 keV) of NGC 1068 is $\sim 10^{44} erg/s$ (Koyama,1989: IAU Symp.,#134) based on the hard-x-ray observation, which can produce $\sim 10^{41} erg/s$ for the S(1) luminosity. This value is 10 times larger than the observed S(1)' luminosity of $\sim 10^{40} erg/s$. If you look at NGC 1068 on face-on-view, you may observe more H_2 emission?

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