Resolving the Rise and Fall of Star Formation in Galaxies
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The Anomalous Ammonia Spectrum of Arp 220

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Abstract. Ultra-luminous infrared galaxies (ULIRGs) are extreme in many ways. The major mergers trigger star formation at very high rates that cause the ISM to be dominated by infrared (IR) photons. We show the ammonia spectra toward the two cores of Arp 220, the nearest ULIRG, in three Very Large Array (VLA) bands (Ku, K, Ka). Typical decay times of the non-metastable transitions ~ 100 s and are therefore usually difficult to observe. The FIR excitation of Arp 220, however, shows that non-metastable states are widely populated up to a limiting energy of ~ 1500 K. We assume that this atypical ammonia spectrum is due to the strong FIR field that re-excites the ammonia molecule on timescales much shorter than the already short decay times. The resulting level population causes a break-down of the typical assumptions made for the use of ammonia as a molecular thermometer.

Keywords. ISM: molecules, galaxies: starburst, galaxies: ISM

1. Arp 220

Arp 220 is the prototypical, and most nearby ULIRG at a distance of only ~ 75 Mpc. This major merger has a star formation rate of hundreds of $M_\odot$/yr, which create a unique, dense, opaque, and energetic environment (Spoon et al. 2004). The large amount of dust largely retains optical and UV emission and even is opaque to the shorter wavelength infrared spectrum. The two starburst cores of Arp 220 merge and will likely create a QSO in the future.

2. The Arp 220 Ammonia Anomaly

The radio continuum reveals the two cores, 'east' and 'west' in Arp 220 (e.g. Barcos-Muñoz et al. 2015). Typically, molecular cm lines are dominated by absorption against the two cores. In most sources, the strengths of metastable $J = K$ ammonia lines and their inversion transitions follow a Boltzmann law in the rotational diagram. The slope of the line represents a temperature. For Arp 220, however, a straight line is not a good fit to the points in the Boltzmann diagram, particular for the western core (see Zschaechner et al. 2016). A 'normal' temperature determination is not possible.

3. Arp 220 K-band Spectrum

Observing the spectra in radio K-band at $\sim 18 - 26$ GHz shows that in contrast to almost any other source, Arp 220 exhibits deep absorption spectra of non-metastable levels, very similar in depth to the metastable lines (Fig. 1). The $J \neq K$ levels are usually

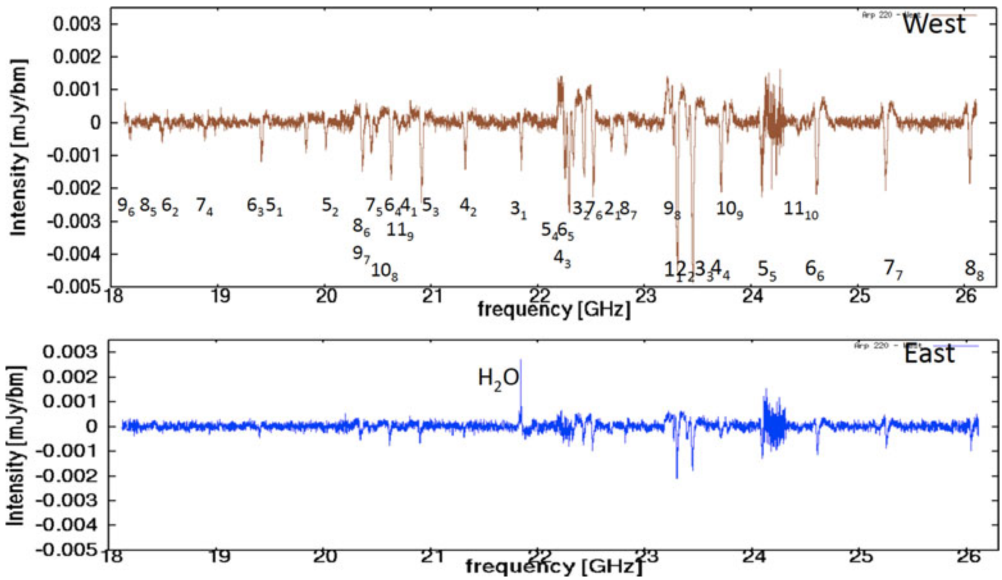

Figure 1. K-band spectra for the two cores in Arp 220.

excited by either collisions or by IR emission, from where they cascade down constant K-ladders. Without constant supply of pumping energy, ammonia would end up in the metastable $J = K$ states, which follow a Boltzmann distribution that is defined by a temperature. The constant pumping inside the strong IR field of Arp 220, however, provides a significant fraction of the gas in non-metastable states. This is particularly true for the western nucleus (see Fig. 1).

4. Ammonia level diagram

If we plot the level diagram of ammonia with K on the x-axis and energy above ground on the y-axis, it turns out that we detect almost all non-metastable lines in K-band up to an energy of about 1500 K (Fig. 2; labeled levels in black). Additional Ka (red) and Ku (blue) data are being observed to fill in essentially the entire level diagram up to that energy and will allow us to derive the most detailed radiative transfer for ammonia in a strong IR field. This will also characterize the use of ammonia as a thermometer under such conditions. The purple lines indicate transitions associated with the first vibrational level.

5. Hidden Water Maser

Our VLA spectrum of Arp 220 (Fig. 1) also reveals a single emission line, which we identify as a 22 GHz water maser line toward the eastern core. Note that the velocities of the cores conspire such that the non-metastable ammonia (3,1) absorption feature of the western core is at the exact same observing frequency. Any unresolved observation would therefore not be able to observe the water maser feature as the two lines largely cancel out (cf. Zschaechner et al. 2016).

6. Additional Lines

Together, the K, Ku, and Ka band observations also provide observations of other molecular lines, including c-C_3H_2, excited OH, the low E_u states of HC_3N, vibrationally

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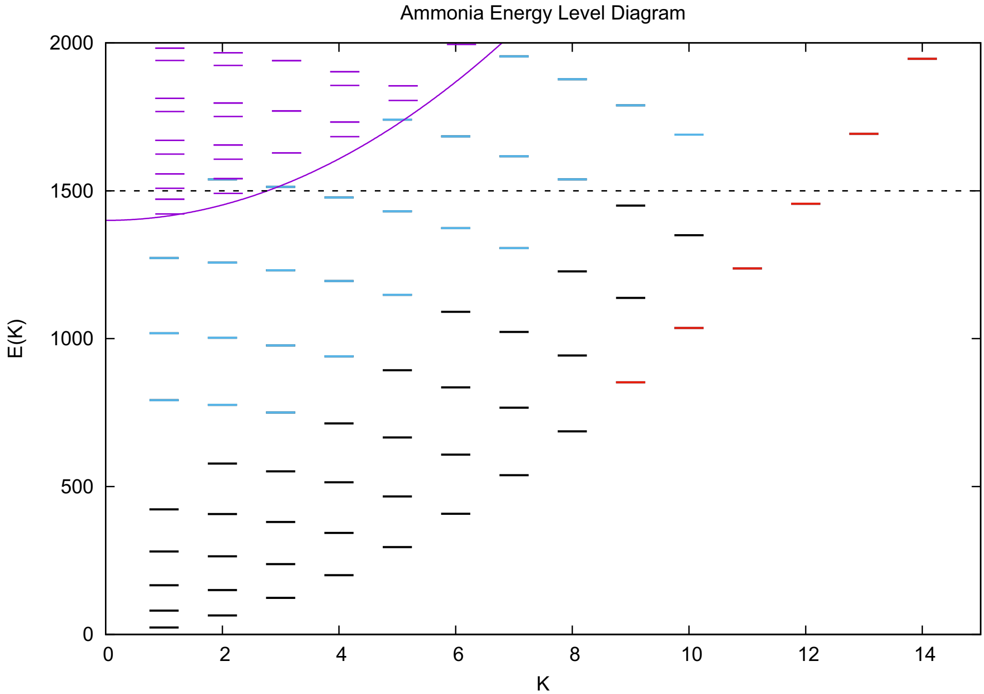

Figure 2. Level diagram for the western nucleus in ammonia in Arp 220. *Black:* Detected transitions, *Blue:* forthcoming observations of non-metastable levels in Ku band to be analyzed, *Red:* forthcoming observation of meta-stable levels observed in Ka band to be analyzed, *Purple outline and levels:* first vibrational excitation states. The dashed horizontal line show the highest excitation energies observed so far.

excited HCN, CH_3OH masers, and H_2CO. These transitions further constrain the excitation of the hot component [OH and HCN (2-1)] as well as any cool component (c-C_3H_2 and HC_3N).

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