Ka-band observations of low-J CO line emission in z$\sim$6 quasar host galaxies

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Abstract

We summarize initial results from our first Ka-band search for weak CO J=2-1 line emission in z$\sim$6 quasar host galaxies. Our sample comprises two quasar host galaxies with redshifts, z=5.77 and 5.85, where both have been previously detected in high-J CO line emission redshifted to the 3 mm band. With these new data we do not detect any CO J=2-1 line emission in our targets, while a tentative detection of strong CO J=2-1 line emission in one source is likely due to baseline structure in the source spectrum which is not fully removed by the vector T_{cal} derived from observations of bright Ka-band pointing and flux calibrators. We outline tests that can be conducted in order to determine the reality of weak, broad extragalactic spectral lines.

Background

The discovery of luminous quasars at z$\sim$6, existing soon after the epoch of cosmic reionization, has opened an exciting new window for the study of the formation and co-evolution of spheroids and black-holes (see Fan, Carilli & Keating 2006 for a review). Follow-up submm/mm-wavelength continuum observations have found that about 30% of the optically selected quasars at these redshifts are hosted by hyperluminous infrared galaxies with large masses of cold dust (e.g. Wang et al. 2007). The molecular gas content of this subsample of the known high-redshift quasar population has been studied, beginning with searches for high-J transitions of molecular CO redshifted to the 3 mm band. These lines are typically broad (a few$\times$100 km/s; see Carilli & Wang 2006), implying that these systems are dynamically massive. As these high excitation emission lines likely arise within warm, dense molecular gas close to the active galactic nucleus (AGN), it is important that complementary studies of the low-J CO emission lines (J=1-0 and J=2-1) be conducted in order to infer the characteristics of the bulk of the cold molecular gas reservoir available to form stars and fuel ongoing AGN activity in these objects. Here, we summarize the analysis and results of the first GBT Ka-band observations of CO J=2-1 line emission in hyperluminous infrared quasars at z∼5.8, where both objects in our sample were previously detected in high-J (J=6-5 and/or J=5-4) line emission with the Plateau de Bure Interferometer (Carilli et al. 2007; Wang et al. *in prep.*).

A summary of the dualbeam single polarization Ka-band receiver commissioning along with a description of the data reduction algorithm used in this analysis are presented in GBT memos 246 and 255.

Observations and Analysis

The observations were conducted using the new subreflector nod observing mode with half-cycle times ranging from 9.0 to 22.5 seconds. We have looked into the effect of different cycle times on the resulting sensitivity and baseline structure, and the results are discussed in the most recent GBT Ka-band commissioning memo (255). The spectrometer was setup so that two 800 MHz spectral windows (hereafter IFs) were tuned to the frequency of the redshifted CO J=2-1 line, with the center of each offset by -100 and +100 MHz, so that they overlapped by 600 MHz. Data were analyzed using new *gbtidl* routines designed specifically to handle Ka-band spectral line observations made while the subreflector was nodding, applying a vector T_{cal} derived from observations of bright calibrator sources (in this case 3c147, 0854+201 and 3c295), to correct for the large-scale baseline structure (scales ∼300 MHz) in the source spectrum created by instrumental artifacts. These are believed to mainly arise after the hybrid in the signal path (see GBT memo 255).

The results of ∼9 hours of on-source observing of CO J=2-1 in the quasar, J0840+5624 at z=5.85 is shown in Figure 1, where a second order baseline has been fit by including the ranges $33.45 < \nu < 33.65$ GHz and $33.8 < \nu < 34.0$ GHz. The line appears at a frequency of ∼33.75 GHz, which is consistent with the redshift of one of the apparently multiple 5-4 line components (though the S/N in the 5-4 line is low and the profile is not well constrained). Another version of this figure, based on a slightly different reduction is shown in Figure 2, where the rms per 50 km/s channel is ∼120 μJy. The theoretical expectation is 130 μJy per channel. The same line is seen in both IFs which overlap by ∼600 MHz. We have subsequently

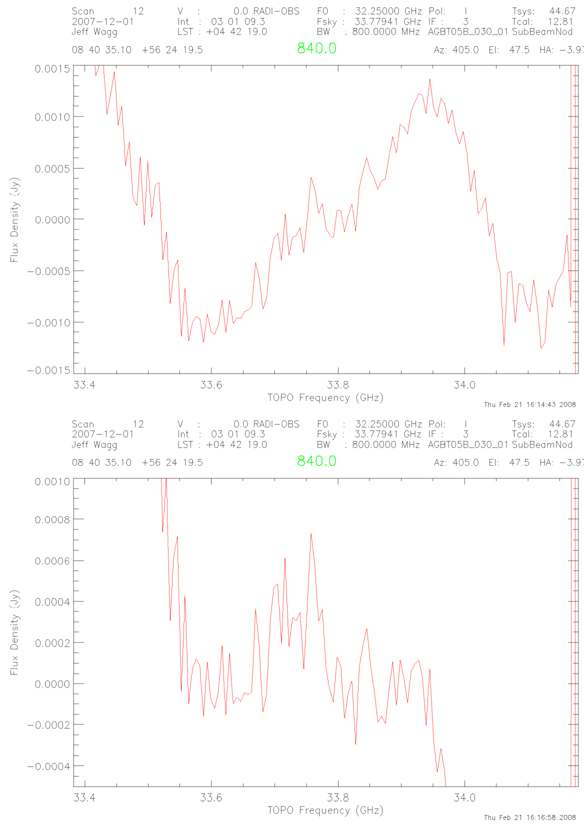

Figure 1: Co-added Ka-band spectra of CO J=2-1 line emission (rest-frame 230.538 GHz) in J0840+5624 redshifted to z=5.83, after ∼9 hrs of on-source observing time, shown before (*top*) and *after* baseline subtraction. The spectral resolution is ∼50 km/s, while a second order baseline has been fit over the 'non-line' regions, $33.45 < \nu < 33.65$ GHz and $33.8 < \nu < 34.0$ GHz.

run different tests to verify the validity of this line, including:

1. moving the line in the IF so that it would appear within different channels,

2. checking that the line is not due to a receiver resonance by processing only the off-source spectrum, treating every second off-source integration as the on-source integration.

For three different IF settings, the same line is seen at the same frequency and with the same intensity as that shown in Figures 1 and 2, confirming that the line is not a spurious feature of the spectrometer. The results of the

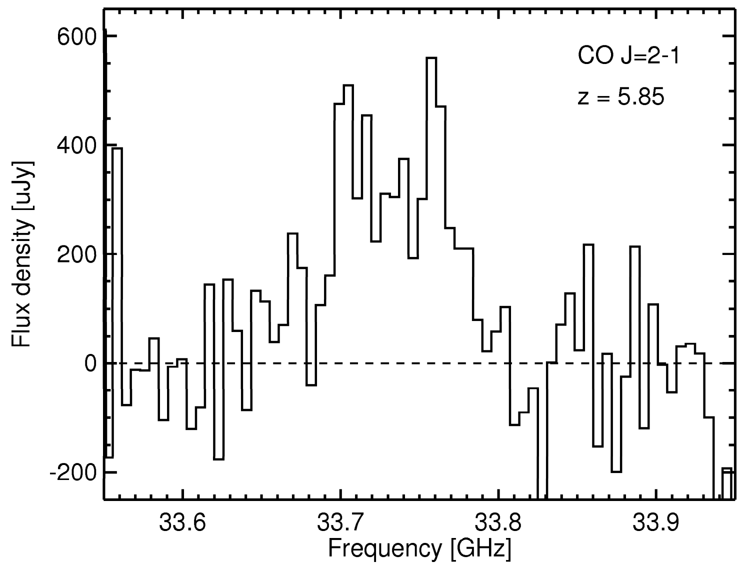

Figure 2: Spectra of a proposed detection of CO J=2-1 line emission in J0840+5624 based on a slightly different reduction than that shown in Figure 1.

second test, the "blank-sky" test, showed no evidence for receiver resonances at these frequencies (Figure 3).

The final test conducted was to determine if a mis-match between the source spectrum and the vector T_{cal} could have led to a spurious detection. We were suspicious that this might be the case because of an apparent dip in the structure of the source spectrum at exactly the frequency of the observed line. This is illustrated in Figure 4, where ~13.5 hours of on-source data have been calibrated with a scalar T_{cal} (average of the vector T_{cal} values), rather than the vector T_{cal}. One can see that the majority of the structure is over relatively large scales (200-300 MHz), though it is suspicious that we see a "dip" at the exact frequency of the proposed emission line. In order to test this, we used the observing time remaining on our second target to continue searching for CO J=2-1 at z=5.77, while at the same time using a second IF pair to search for CO J=2-1 at the frequency observed in the first source (z=5.85). The results are shown in Figure 5, where we show the spectra of both sources after ~4 hours of observing with the same spectrometer setup (though the sensitivity is worse for the data taken on the second target, observed under conditions of high opacities). In both cases we fit baselines in an identical fashion (second order polynomials) and the data suggest that the same emission line is seen in both sources at the same frequency. The

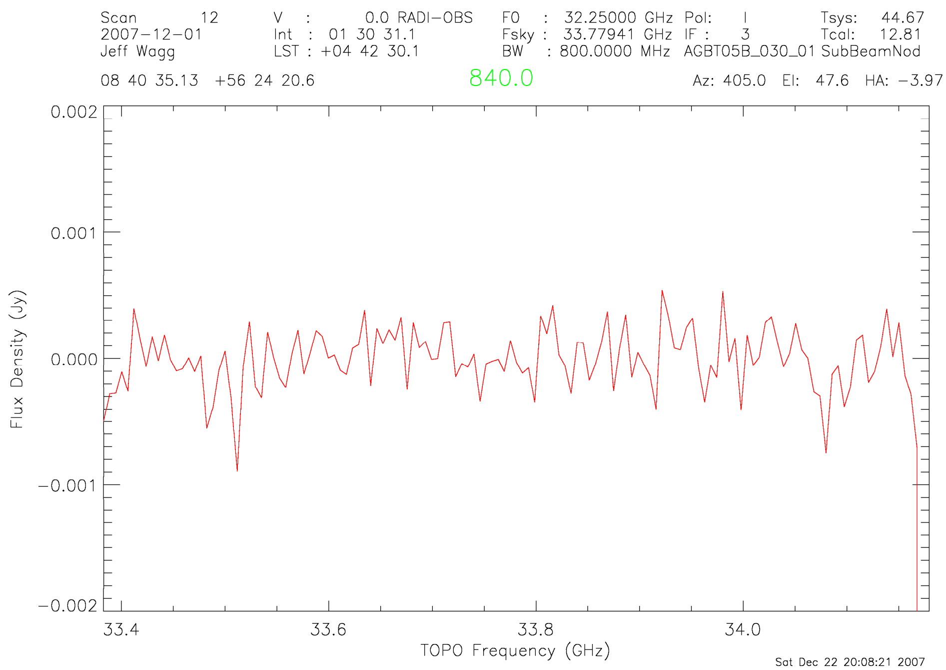

Figure 3: Result of processing only the off-source spectra (ie. on-sky) in order to test whether a receiver resonance could produce the spurious line shown in Figure 2.

results of this final test would suggest that the line is likely due to small scale structure in the source spectrum which is not fully removed by the vector T_{cal}.

Although we do not yet know why the vector T_{cal} is not sufficient to remove this small-scale structure in the source spectrum, there are at least two possibilities that observers should be aware of. Before being applied the vector T_{cal} is smoothed (in this case on scales of 3 MHz), while this smoothing scale will not be able to remove features which are narrower than the smoothing width. There also remains a ∼60 mK difference in power between the 'On' and 'Off' integrations in a subreflector nod observation. Any difference in power will produce a ghost of T_{sys} in the results. In this particular case, we do not know that a δT of this magnitude is sufficient to produce what we see.

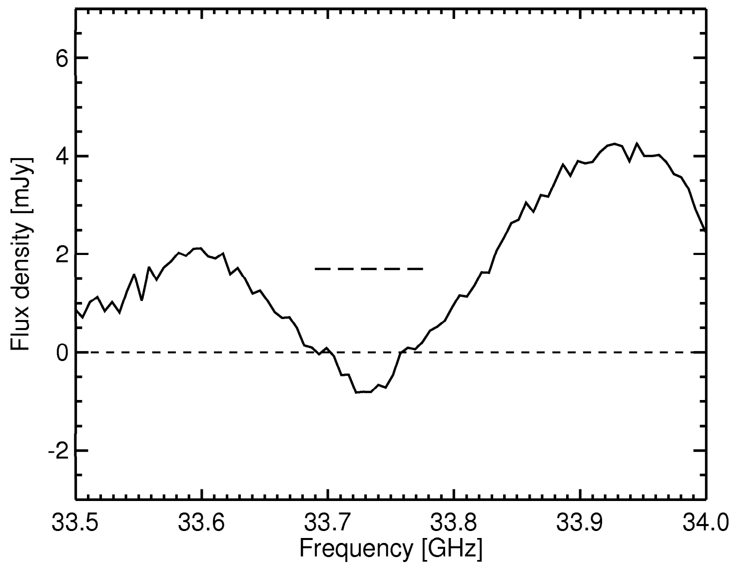

Figure 4: Resulting spectra of J0840+5624 after ∼13.5 hrs of on-source integration time, when a scalar, rather than a vector T_{cal} is applied. The region of proposed line emission is denoted by the *long-dashed* line.

Conclusions

We have presented the initial results of a search for CO J=2-1 line emission in quasar host galaxies at z∼6. The spectral baselines are in general found to be good, with residual structure on typical scales that are typically larger than those expected for high-redshift spectral emission lines. However, we find that it is possible to create spurious spectral lines at some frequencies where mismatches between the source spectrum and vector T_{cal} used to improve spectral baselines.

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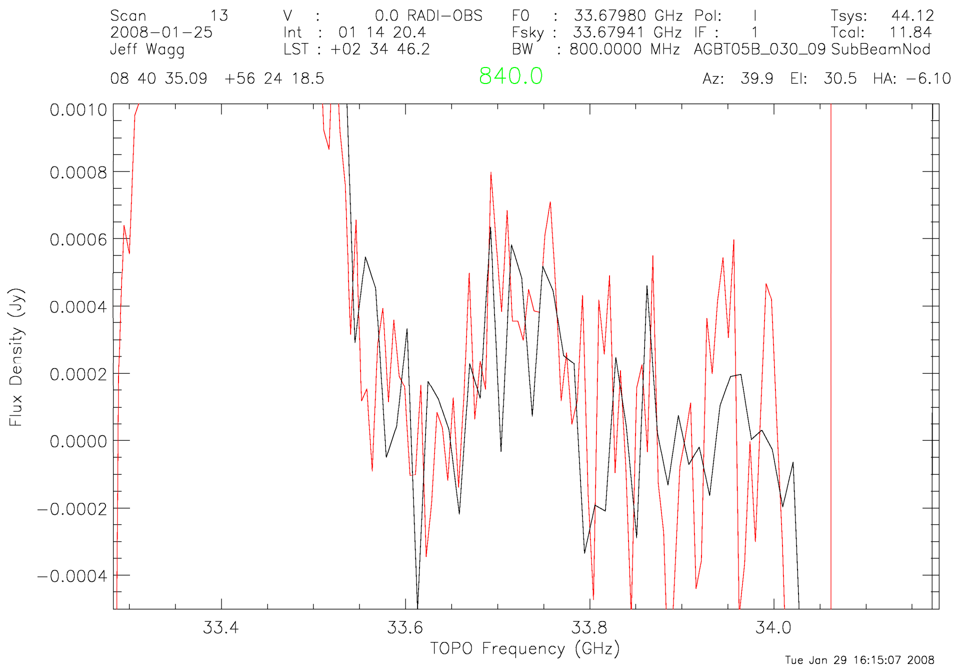

Figure 5: Spectra of both J0840+5624 (*red* line) and J0927+2001 (*black* line) after 3.5–5.0 hours of on-source integration time per source. Spectral baselines have been fitted and removed using a second-order polynomial fit over the same regions in each spectra. Evidence for the CO J=2-1 emission line originally believed to have been detected in J0840+5624 is also seen in the spectra of J0927+2001 yet the CO redshift of this second quasar derived from detections of CO J=5-4 and J=6-5 line emission is z=5.77.