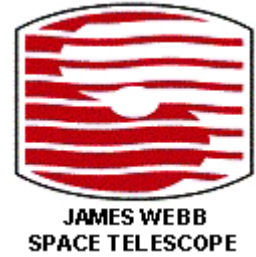


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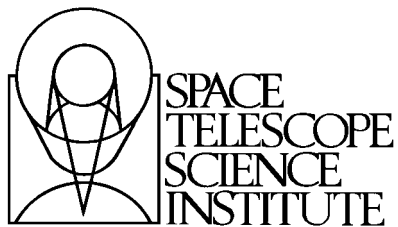
Space Telescope Science Institute  
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## Astronomical Sources as Line Calibrators

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Astronomical Sources as Line Calibrators

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## 1.0 Introduction

On-board calibration lamps present some significant challenges for an infrared telescope. In order to maintain the cryogenic temperatures necessary to enable the proposed science, the lamps would need to operate at cryogenic temperatures and the heat generated by the lamps would need to be dumped efficiently. The possibility of simplifying the design and operation of the instrument by using astronomical sources in lieu of lamps is thus an appealing alternative, especially for line sources.

Indeed, the recent infrared missions ISO and SIRTf have chosen to forgo internal line sources in their spectrographs, instead using a combination of instrument models and external sources for their spectral calibration. However, the calibration requirements for JWST are substantially more demanding than for the ISO and SIRTf spectrographs, especially because of the two-dimensional aperture plane of both the near-infrared spectrograph NIRSPEC and the Integral Field Unit (IFU) of the mid-infrared instrument MIRI.

Since the design of the NIRSPEC is not yet finalized, we characterize its calibration needs in generic terms. We assume that the NIRSPEC includes a large number ( $\sim 10^6$ ) of individually selectable apertures. In principle, we need to calibrate for each aperture and each spectral mode a) where the spectrum falls on the detector, including wavelength zero point, function, and trace, b) the transfer function, or overall system throughput as a function of wavelength; and c) the contrast, or the total throughput with the slit closed. Many of these calibrations can be carried out simultaneously for a large number of apertures, and therefore can take advantage of extended line sources; however, since the spectra from different apertures overlap, sources with strong line-to-continuum ratio are needed to calibrate apertures efficiently. The MIRI IFU shares the two-dimensional nature of NIRSPEC, and thus similar considerations apply; however, since spectra from different apertures do not overlap, a strong line-to-continuum ratio is not a requirement. Point sources will in general suffice for the MIRI slit-spectrograph mode.

As described in Casertano (2001), we will assume that several of the characteristics of the spectrographs can be described by slow functions of position in the focal plane and of wavelength. For example, one could expect that the total throughput and the wavelength zero point vary from subaperture to subaperture as a consequence, e.g., of manufacturing variations; however, the wavelength mapping depends primarily on the optics and dispersive elements between the aperture and detector plane, and thus can be expected to vary smoothly with aperture position, and be essentially unaffected by the precise location and shape of each aperture. Therefore the goal of the NIRSPEC and MIRI calibration programs is to construct an instrument model that accounts for small scale variations of quantities that depend on the details of each aperture, and large-scale variations of other quantities. This approach results in a manageable calibration program; if the underlying assumptions of instrument modelability are not satisfied in practice, calibration of the spectrographs may prove substantially more difficult, and may well require project-specific calibrations.

In this report, we discuss and begin to quantify the use of astronomical sources to calibrate the throughput, wavelength zero point, wavelength solution, spectral trace, and line profile of the spectrographs on JWST. Each instrument/mode combination has specific requirements on the type of target that can be considered suitable. Line profile calibration requires a point source with a bright, narrow line in the appropriate region of the spectrum. The wavelength zero point calibration requires a source with one or few dominant lines, and the wavelength dispersion solution requires a source with multiple lines of comparable strength in the relevant region of the spectrum. For both, the calibration of NIRSPEC and IFU can be much more efficient if the line source is extended. The throughput calibration of both spectrographs are best carried out with a continuum sources of known spectral energy distribution; a point source for the slit spectrograph, and extended sources for the two-dimensional units, the latter combined with a spectrophotometric standard to calibrate the spectral energy distribution, and broad-band images to measure brightness variations. Observations of line sources—possibly calibrated via narrow-band filter observations—are useful checks of the total throughput calibration. A number of techniques can be used to carry out the actual calibration program; see Casertano (2001) for a discussion.

This document is not intended as an exhaustive summary of all suitable targets and calibration options, but rather as a sanity check undertaken to establish the existence of any suitable targets. The relevant criteria depend on the specific calibration, but they include line wavelength, flux, and intrinsic width, source size and uniformity (filling factor), and continuum flux. We expect to extend this analysis to continuum sources in a future document.

### *1.1 Suitable astrophysical sources*

A wide variety of astrophysical sources could make good candidates for the types of calibrators needed by JWST. In this exploratory study, we have considered representatives of five promising classes, both point and extended sources: emission-line stars, reflection nebulae, star forming regions, planetary nebulae, and supernova remnants. A sixth class, galaxies with central emission-line regions, yields less promising candidates and is not discussed further here. Desirable characteristics for astronomical line calibrators include strong, well-defined lines, high line-to-continuum ratio, and, for extended sources, spatial extent matched to the JWST field of view with reasonably uniform surface brightness. Unlike artificial sources, which can often be assumed to be smooth on small angular scales (tens or hundreds of pixels), extended astronomical sources will in general exhibit surface brightness variations on a broad range of scales, and cannot be assumed to be smooth – although in general the luminosity pattern can be assumed to remain constant in time over a typical set of observations. Therefore, using astronomical sources as extended calibrators requires techniques that do not make strong assumptions on spatial variation. For example, the self-calibration technique introduced by Fixsen et al. (2000) relies on solving for both detector properties and surface brightness distribution at the same time; we assume that similar techniques can be employed, when necessary, for the calibrations discussed here. Such techniques work best when the source has a high filling factor, so that most pixels exposed to the source will collect an adequate amount of signal; note however

that with very few exceptions, the filling factor of a source at JWST resolution can only be measured with JWST observations.

### ***1.2 Sparse or Dense Apertures?***

In the case of NIRSPEC, two fundamentally different modes of calibration can be employed, depending on the nature of the source and on the type of calibration desired. In what we call the ‘sparse aperture’ mode, apertures are turned on with the same constraints as for a typical science observation, i.e., so that individual apertures produce non-overlapping spectra. In this mode, each aperture produces an independent spectrum; up to a few hundred apertures can be calibrated simultaneously (fewer for  $R \sim 1000$ ). The ‘dense aperture’ mode consists of turning on individual slitlets in a dense pattern, such as one slitlet in each  $3 \times 3$  or  $4 \times 4$  square; with such a pattern, all slitlets can be calibrated in 9 or 16 exposures. This mode can be used if there is no wavelength dispersion, e.g., in ‘mirror’ mode, to identify the location corresponding to each aperture in the detector plane. It can also be used if the spectrum produced by each source is essentially monochromatic, so that each aperture produces a single spot in the spectrum. If the spectrum contains a small number of lines with little continuum, a somewhat less dense pattern in the spectral resolution direction can be employed to avoid overlaps of individual lines from different apertures. A dense aperture pattern can also be employed with an extended continuum source in conjunction with a narrow-band filter.

The advantage of using a dense aperture pattern is that it allows the calibration of every individual aperture in a manageable number of observations. If dense patterns cannot be employed, only a few hundred apertures at most can be calibrated in each observation, and therefore individually calibrating all  $\sim 10^6$  apertures is essentially impossible. Whenever a sparse aperture pattern is employed, individual apertures must be calibrated either ‘as needed’ or statistically, as part of a global instrument model. One of the advantages of artificial calibration sources is that they can be designed to facilitate calibration with dense aperture patterns.

## **2.0 The Targets**

We have collected available data for sources in five broad classes: emission-line stars, supernova remnants, reflection nebulae, planetary nebulae, and star-forming regions. The potential targets and related references are listed in Tables 1 through 5; see also the flux summary in Table 6. The relevant reference material has been collated into an extensive Atlas (Holfeltz and Casertano 2003).

From the Tables, there appears to be a relative dearth of information in the range  $2.5\text{-}5 \mu\text{m}$ . We have not investigated this lack of data in detail, but it probably reflects the current status of observations rather than any fundamental issue with this wavelength range. Ground-based observations have been traditionally considered more difficult beyond  $2.5 \mu\text{m}$ , and space missions have emphasized wavelengths beyond  $5\text{-}10 \mu\text{m}$ . The issue of overall wavelength coverage should be investigated again in a few years, after the results of SIRTf and more ground-based efforts.

**Table 1. Emission-line Stars**

ID (Notes)	Type	Wavelength Coverage ( $\mu\text{m}$ )	References
RX J0019.8+2156 (variable)	Ss	1.0 - 2.4	Quaintrell & Fender 1998
BD +29 4453	B1.5V	1.53 - 1.69	Steele & Clark 2001
CD -27 11872	B0.5V-III	1.53 - 1.69	Steele & Clark 2001
BD +54 2348	B2V	1.53 - 1.69	Steele & Clark 2001
MWC 659	BOIIIpe	1.53 - 1.69	Steele & Clark 2001
$\gamma$ Cassiopeiae (star in nebula)	Be	2 - 13	Hony et al. 2000, Rinehart et al. 1999
CI Cam / XTE J0421+560	B[e] / X-ray binary	1.0 - 2.5	Clark et al. 1999
$\beta$ Lyr	Be	8.0 - 13.3	Rinehart et al. 1999
WR122	Ofpe/WN9?	1.45 - 1.8, 2.0 - 2.4	Figer & McLean 1997, Morris et al. 1996
He 3-519	LBV	2.0 - 2.28	Morris et al. 1996

**Table 2. Supernova Remnants**

ID	Wavelength Coverage ( $\mu\text{m}$ )	References
Crab Nebula FK Position 6	0.94 - 1.30	Rudy et al. 1994
Crab Nebula FK Position 10	0.94 - 1.30	Rudy et al. 1994
Cas A: FMK 1	0.95 - 2.4	Gerardy & Fesen 2001
Cas A: QSF 1	0.95 - 2.4	Gerardy & Fesen 2001
Cas A: QSF 2	0.95 - 1.8	Gerardy & Fesen 2001
Cas A: QSF 3	0.95 - 1.8	Gerardy & Fesen 2001
Kepler (west rim knot)	0.95 - 2.25	Gerardy & Fesen 2001
3C 391: Southern OH 1720 MHz maser	5 - 16	Reach et al. 2002
3C 391:BML molecular shock front	5 - 16	Reach et al. 2002
3C 391:BML ionic shock front	5 - 16	Reach et al. 2002

**Table 3. Reflection Nebulae**

ID	Size (arcmin)	Central Star ID (Spectral Type)	Wavelength Coverage ( $\mu\text{m}$ )	References
vdB 17 / NGC 1333	3	BD+30 549 (B8 V)	1.2 - 2.3, 5 - 15	Martini et al. 1999, Uchida et al. 2000
vdB 59 / NGC 2068	4	HD 38563B (B2 II-III)	1.2 - 2.3, 5 - 15	Martini et al. 1999, Uchida et al. 2000
vdB 133	4	HD 195593 A+BF5 (Iab + B7 II)	5 - 15	Uchida et al. 2000
NGC 2023	9	----	1.2 - 2.3	Martini et al. 1999
NGC 7023	9	----	1.2 - 2.3	Martini et al. 1999

**Table 4.** Planetary Nebulae

ID	Diameter (arcsec)			Central Star (Type)	Wavelength Coverage ( $\mu\text{m}$ )	References
	Optical	IR	Radio			
NGC 6153	24			HD 148687	7.5 - 23	Pottasch et al. 1986
NGC 6302	44.5	20	10	HD 155520	2.4 - 120	Beintema & Pottasch 1999, Molster et al. 2001, Persi et al. 1999, Pottasch et al. 1986
NGC 6543	19.5	20	15	HD 164963 Of/WR(H)	1.2 - 2.4, 5 - 23	Hora et al. 1999, Persi et al. 1999, Pottasch et al. 1986
NGC 7009						Pottasch et al. 1986
NGC 7027	14	20	15	HD 201272	1.2 - 2.5, 4 - 15.6	Hora et al. 1999, Lumsden et al. 2001, Persi et al. 1999
G79.29+0.46		300			4.02 - 4.08	Waters et al. 1996
M 1-4	4		6	AG82 22	1.6 - 2.5	Lumsden et al. 2001
M 1-1	6		5	AG82 10	1.6 - 2.5	Lumsden et al. 2001
K 3-67			2.2	AG82 34 O(C)	1.6 - 2.5	Lumsden et al. 2001
Vy 1-1	5.2		6	AG82 3	1.6 - 2.5	Lumsden et al. 2001
Pc 12	4.6		1.8	AG82 214	1.6 - 2.5	Lumsden et al. 2001
M 1-14			4.7		1.6 - 2.5	Lumsden et al. 2001
M 1-6	5		2.9		1.6 - 2.5	Lumsden et al. 2001
$\eta$ Car					0.7 - 0.9 1.04 - 2.29	Hamann et al. 1994
IC 418	12			HD 35914 Of(H)	1.0 - 2.4	Hora et al. 1999
BD +30 3639	7.5	12	8	HD 184738 WC 9	1.2 - 2.4, 8 - 22	Hora et al. 1999, Lumsden et al. 2001, Pottasch et al. 1986
Hb 12	1		0.7	AG82 452 WN 7?	1.2 - 2.4	Hora et al. 1999
IC 5117	1.2		1.5	HD 205211 WR	0.80 - 2.4	Rudy et al. 1994

**Table 5.** Star-forming Regions

ID	Comments	Size (arcmin)	Wavelength Coverage ( $\mu\text{m}$ )	References
Pistol Star	Star in nebula		1.1 - 2.4	Figer et al. 1998
NGC 2071	H II region; SFR		2.06 - 2.38	Walther et al. 1991
Orion Peak 1	Bright H <sub>2</sub> emission peak of the Orion OMC-1 outflow		2.5 - 50	Rosenthal et al. 2000

### 3.0 Example of line sources as calibrators

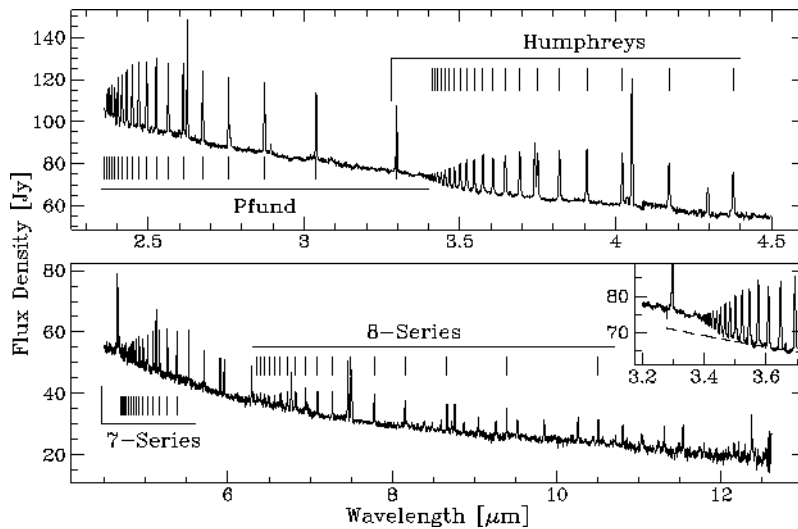
In order to consider how sources of each of the classes above would serve as line calibrators, we discuss in detail a representative case for each of the five categories, typically the promising target with the best available data. We consider the following sources:

1. Emission-line stars:  $\gamma$  Cas
2. Supernova remnants: Cas A
3. Reflection nebulae: NGC 1333
4. Planetary nebulae: NGC 6543
5. Star-forming regions: Orion Peak 1

#### 3.1 Emission-line stars: $\gamma$ Cassiopeiae

Be stars, or B stars with optical emission in hydrogen Balmer lines, are a very promising source of line calibrators in the near- and mid-infrared. Rinehart et al. (1999) have identified a multitude of hydrogen recombination lines in the wavelength region between 8 and 13  $\mu\text{m}$  for 11 luminous Be stars, with continuum emission ranging from about 0.1 to 50  $10^{-14}$   $\text{erg}/\text{cm}^2/\mu\text{m}$ . As an example of these stars, we consider  $\gamma$  Cassiopeiae, which was observed with the ISO short-wavelength spectrograph (SWS) in the range 2.5-45  $\mu\text{m}$ ; Hony et al. (2000) present the results of these observations in the range 2-12  $\mu\text{m}$ . Its infrared spectrum is dominated by numerous emission lines from hydrogen, with a few helium lines also visible. The emission region is only a few stellar radii in size, and therefore can be assumed to be a point source at JWST resolution. Typical line fluxes are several  $10^{-11}$   $\text{erg}/\text{cm}^2/\text{s}$ , and most lines are under 250 km/s FWHM—although some lines show broader widths, up to 700 km/s. Lines are therefore completely unresolved at  $R=100$ , and most are only marginally resolved at  $R=1000$ .

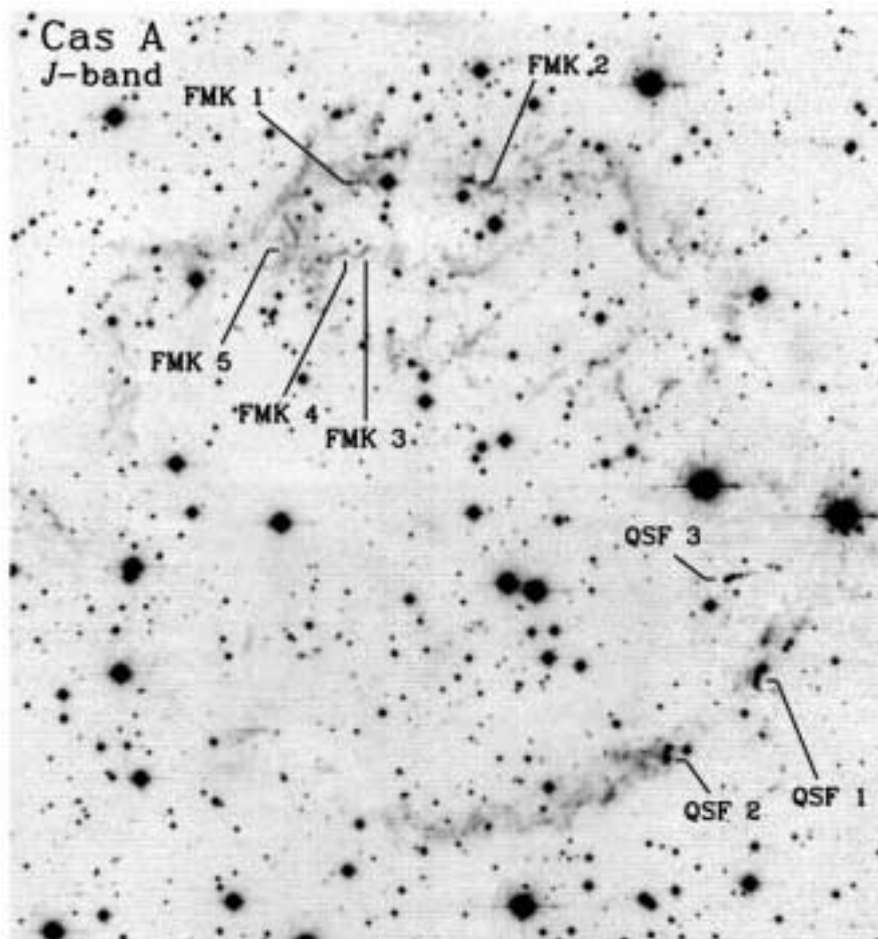
**Figure 1:** ISO SWS spectrum of  $\gamma$  Cassiopeiae (Hony et al 2000)



As a JWST calibrator,  $\gamma$  Cassiopeiae presents several attractive features. It is very bright both in line and in continuum, and therefore it can be readily observed in very short

exposures. It has a multiplicity of lines with well-defined wavelengths—most lines are part of the standard H recombination transitions, from  $m=10 - 20$  down to  $n=4 - 10$ . The lines cover most of the relevant spectral region for both NIRSPEC and MIRI, and are numerous enough to provide a very good wavelength solution. Because of the point-source nature of the emitter and of the intrinsic width of the lines, the source will be useful as a line-shape calibrator at least at the lower resolution ( $R=100$  for NIRSPEC, and  $R=300$  for MIRI), although it may not be suitable for line-shape calibration at high resolution ( $R=1000$  and  $3000$ , respectively). It is also possible that  $\gamma$  Cassiopeiae may prove unsuitable as a calibrator because of its excessive brightness. However, Be stars are not uncommon, and it should not be difficult to find another target with a more suitable luminosity and possibly line width.

**Figure 2:** J-band image of the Cas A supernova remnant (from Gerardy and Fesen 2001)

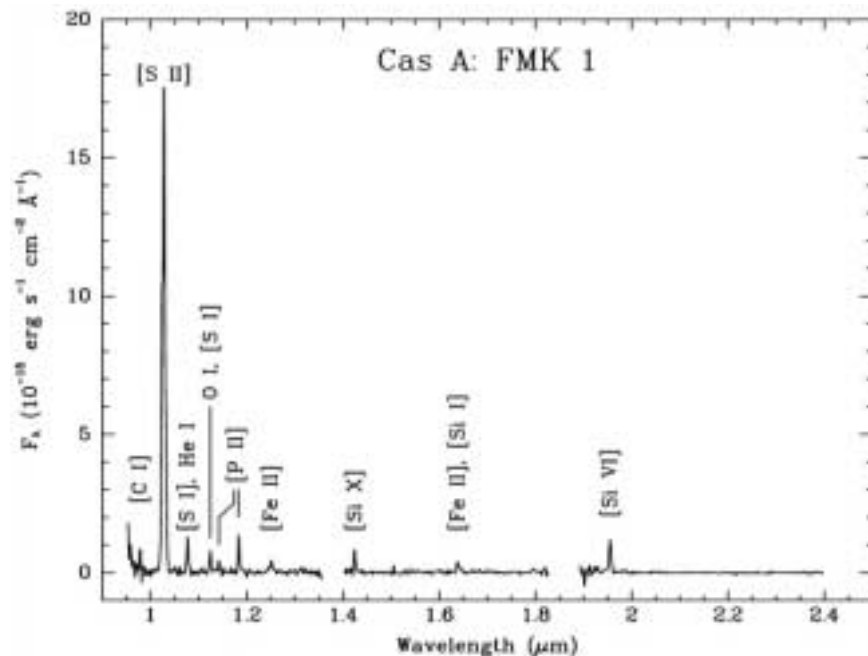


### 3.2 *Supernova remnants: Cassiopeia A*

Cassiopeia A, the youngest known Galactic supernova remnant, is a shell-like nebula with a total angular extent of  $6.5'$ . Ground-based near-infrared imaging and spectroscopy recently obtained by Gerardy and Fesen (2001) in the wavelength range  $0.95-2.4 \mu\text{m}$  has

shown knots of strong line emission, as well as diffuse continuum emission primarily in the K band. The authors identify about a dozen well-defined, narrow lines in the fast-moving knots (FMK) located in the Northern part of the nebula, and over twenty lines, primarily due to [FeII], in three quasi-stationary floccules (QSF) near the Southern rim of the nebula. Line fluxes are in the range  $10^{-14}$  to  $10^{-12}$  erg/cm<sup>2</sup>/s; the lines in the QSF appear unresolved in these observations ( $R=700-1400$ ), while the emission in the FMK appears to be resolved in wavelength. The authors do not comment on the velocity width of individual features; Doppler shifts may be significant, since observed wavelengths are up to  $0.005 \mu\text{m}$  from the nominal values, and each feature must be wavelength-calibrated. On the other hand, the regions of diffuse luminosity, especially in K band, show no indication of significant line emission, indicating that the emission is probably continuum; on the basis of the estimated local physical conditions and of the similarity of the K-band structure of the nebula to its radio emission features, the authors suggest that diffuse NIR emission may be due to IR synchrotron radiation.

**Figure 3:** NIR spectrum of Fast Moving Knot 1 in Cas A (Gerardy and Fesen 2001)



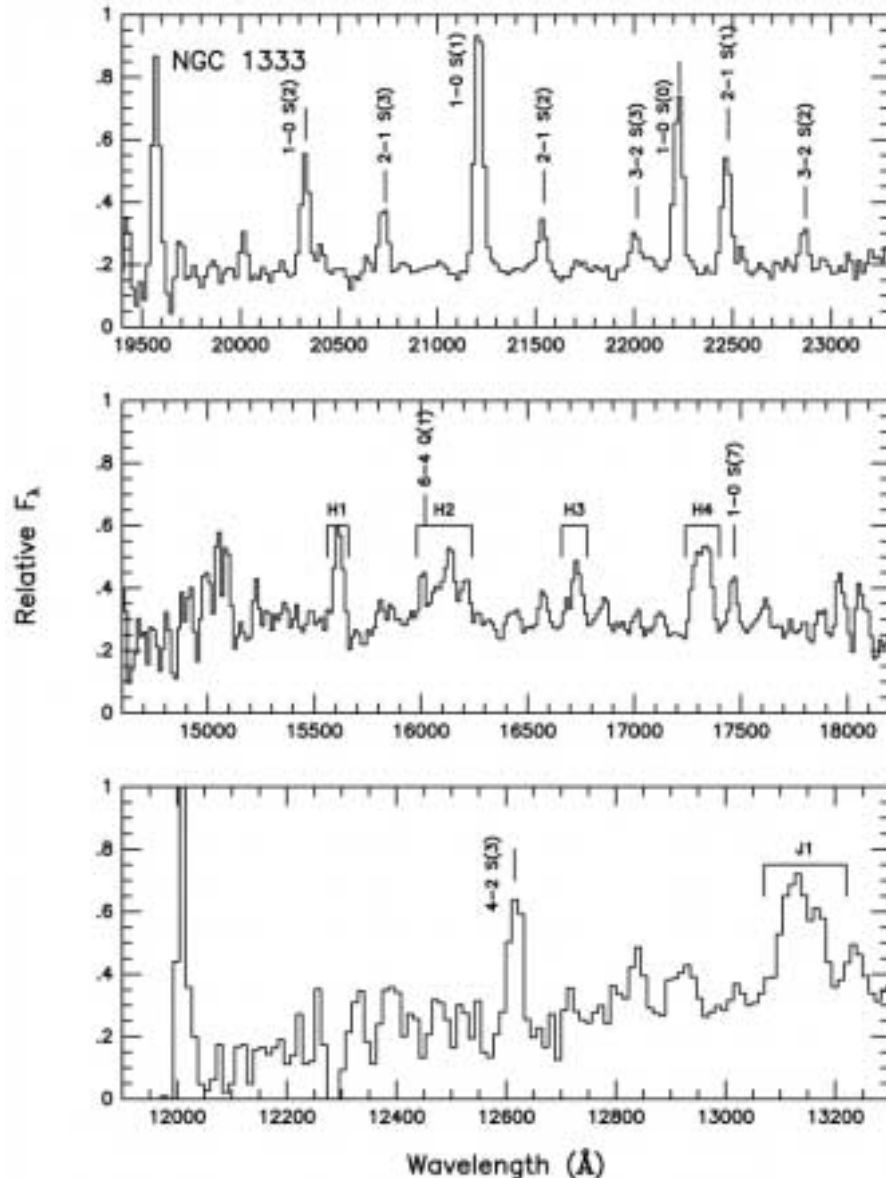
A supernova remnant like Cas A may not be particularly well-suited as a line calibrator for JWST, since the line emission is concentrated in small regions. However, other supernova remnants may prove to have extended IR line emission; see for example RCW 86, for which Rosado et al. (1996) detect extended H $\alpha$  emission on scale of several arcminutes at  $9''$  resolution.

### 3.3 Reflection nebulae: NGC 1333

Reflection nebulae are extended sources that shine primarily by reflecting the light of luminous stars. Several known nebulae exceed  $5'$  in angular size, and thus such nebulae

can readily fill the field of view of JWST instruments. Nearly 300 nebulae are listed in Lang (1991). Their usefulness for JWST is in that they present strong, diffuse NIR line emission, especially in fluorescent lines of molecular hydrogen, with line-to-continuum ratio of several at the line peaks. The lines appear to be intrinsically narrow and well-defined, and therefore can be used to calibrate the line position of NIRSPEC. They also present several emission features in the 3.5-12  $\mu\text{m}$  region, but these features are broad in wavelength and are not useful as line calibrators.

**Figure 4:** NIR spectrum of a 45'' wide region of NGC 1333 (Martini et al. 1999)



As example of a reflection nebula we consider NGC 1333 (vdB 17), a 3' region surrounding the B8:p star BD +30 549 (Martini et al. 1999, Uchida et al. 2000). This nebula shows 9 clearly defined lines in the K window alone, with line-to-continuum ratios up to

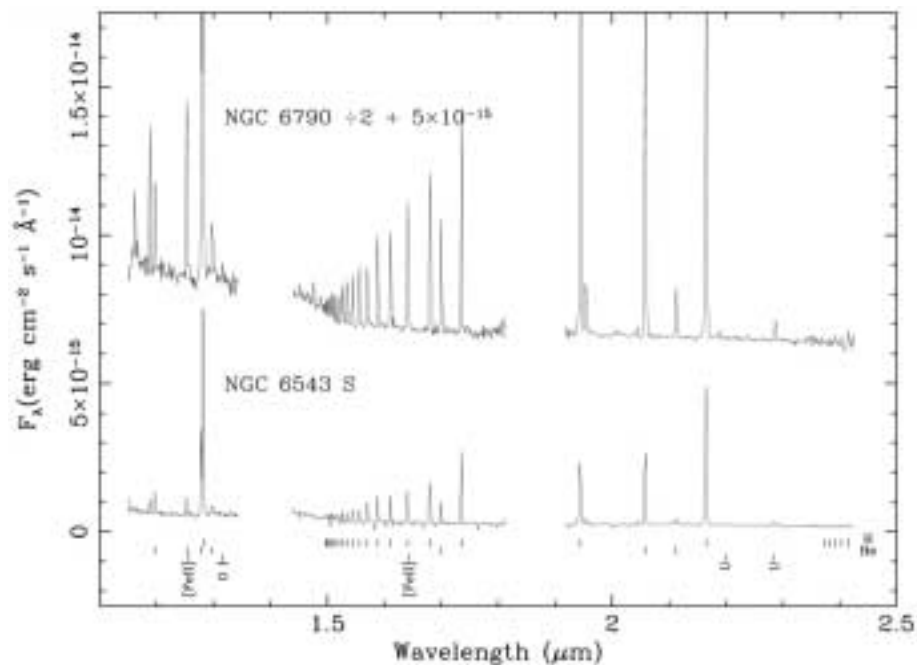
4:1; weaker lines are also seen in the J and H windows. Many of the lines appear essentially unresolved in the observations ( $R \sim 550$ ). The ISO spectrum covering the range 5-15  $\mu\text{m}$  shows several broad features, however because of the insufficient resolution it is not clear that NGC 1333 can be a useful source of line calibration in the mid-infrared.

The multiple narrow lines around 2  $\mu\text{m}$ , the good spatial extent and filling factor, and the high surface brightness make NGC 1333 a good calibration target for NIRSPEC. However, the low line-to-continuum contrast means that it will not be possible to use dense aperture mode for this source. Instead, NGC 1333 must be observed in sparse aperture mode, just as typical science targets would. In this mode, NGC 1333 – and other reflection nebulae – can be used as a quick and efficient check of the wavelength zero point and wavelength solution.

### 3.4 Planetary nebulae: NGC 6543 (the Cat's Eye nebula)

Planetary nebulae are diffuse, optically thin clouds surrounding a very hot star in the late stages of its pre-white dwarf evolution. The emission in planetary nebulae is concentrated in very narrow lines, with essentially no continuum emission away from the central star. Planetary nebulae in the Milky Way range in size from a few arcseconds to several arcminutes, with some nebulae ranking among the most spectacular objects observed with HST.

**Figure 5:** Near-infrared spectrum of two planetary nebulae (Hora et al. 1999)



The prominent feature of planetary nebulae as line calibrators is the extended line emission with no continuum and very narrow intrinsic width. Because of these properties, planetary nebulae can be used as multiplexed calibrators for both wavelength zero point and wavelength solution as a function of field position, possibly using the efficient dense

aperture mode. On the other hand, the luminosity is uneven, with changes and structure down to sub-arcsecond scales; planetary nebulae are thus not good sources for pixel-to-pixel line flux calibration. Some nearby planetary nebulae vary in size over time, by up to several mas/year, because of their geometric expansion; their expansion, although small, must be considered in time-dependent calibrations. Expansion velocities are small, typically  $< 20$  km/s.

As an example of planetary nebulae we consider NGC 6543, the Cat's Eye nebula. NGC 6543 is about  $20''$  across, and has a beautiful (and irregular) structure in the visible, with strong emission in  $H\alpha$  and in lines of [OIII], [NII] and [SIII]. Infrared spectra obtained by Hora et al. (1999) show several very narrow lines in the H and K bands, mostly hydrogen Brackett lines and HeI series, with no indication of an extended continuum. The line flux in the  $1'' \times 6''$  slit ranges from 0.5 to  $70 \times 10^{-14}$  erg/cm<sup>2</sup>/s; the brightest lines would produce several tens of counts/second/JWST pixel. Low-resolution ( $R \sim 14$  to 35) IRAS/LRS spectra show evidence of strong features corresponding to [ArIII], [SIV], [NeIII] and [SIII] transitions, with total flux up to  $5 \times 10^{-10}$  erg/cm<sup>2</sup>/s (Pottasch et al. 1986); however, the quality of the spectra is not sufficient to estimate reliably what JWST would observe. Note that NGC 6543 was the primary calibrator for LRS.

Despite its irregular shape and relatively low filling factor, a planetary nebula such as NGC 6543 would offer a very good target for dense aperture mode calibrations, thanks to its extended nature, high line flux and low (or zero) continuum. A fairly short (10-100s) exposure with NIRSPEC would produce high S/N, essentially monochromatic spots corresponding to each open aperture, thus allowing to calibrate the position of each spectrum in both spatial and wavelength directions. Such calibrations may be much more efficient than sparse aperture mode calibrations, even accounting for the loss of efficiency due to the target's small size and irregular surface brightness distribution.

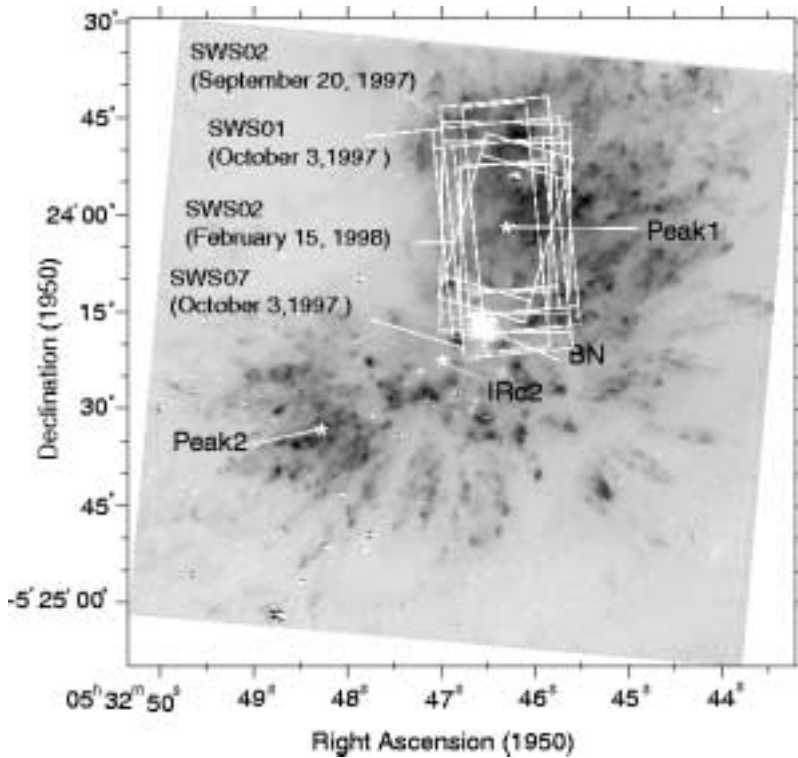
### ***3.5 Star forming regions: Orion Peak 1***

Star-forming regions are probably the most varied class of extended line sources. Even different areas within a single region, such as Orion, differ enormously in their properties. We have considered the Orion Peak 1 region, which corresponds to the bright  $H_2$  emission peak in the Orion OMC-1 outflow, primarily because of the availability of NICMOS narrow-band imaging in the  $H_2$  1-0 S(1) transition (Schultz et al. 1999) and of ISO SWS spectra (Rosenthal et al. 2000).

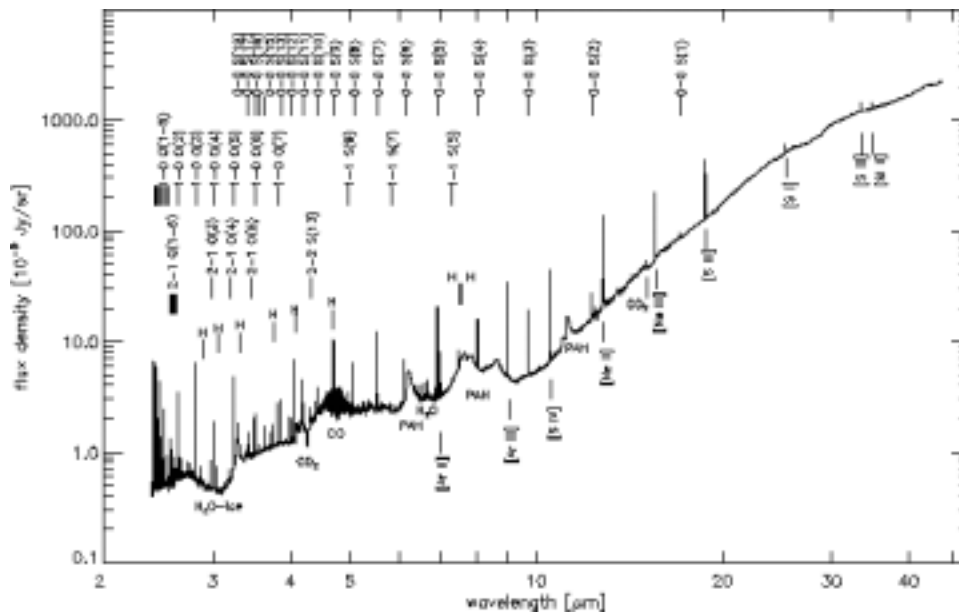
The line emission covers a region about  $1'$  in size, and includes a diffuse component as well as bright, unresolved knots. The ISO SWS spectrum was taken through a  $14'' \times 20''$  aperture shortward of  $12 \mu\text{m}$ , and a  $14'' \times 27''$  aperture between  $12$  and  $27.5 \mu\text{m}$ . The SWS spectrum includes a significant amount of continuum flux, but the authors indicate that much of the continuum may be generated by a single bright source. The line spectrum of

the Peak 1 region is dominated by a large number of narrow rotational and roto-vibrational H<sub>2</sub> lines, together with significant HI and fine structure lines.

**Figure 6:** NICMOS image of Orion Peak 1 (Schultz et al. 1999, Rosenthal et al. 2000)



**Figure 7:** ISO SWS spectrum of Orion Peak 1 (Rosenthal et al. 2000)



The authors conclude that two separate components are present: the H<sub>2</sub> emission comes from the shock-excited gas within the star-forming molecular cloud, while the

atomic hydrogen and fine structure lines originate in the foreground HII region. The brightest lines have total flux of up to  $7 \times 10^{-11}$  erg/cm<sup>2</sup>/s in the aperture; if uniformly distributed over the ISO aperture, the corresponding line signal yields a few hundred e/s per NIRSPEC aperture. The continuum flux rises steadily from 2.5 Jy at 2.5  $\mu$ m to 4000 Jy at 27.5  $\mu$ m; at the highest resolution of the ISO SWS, the peak line-to-continuum ratio is about 10 to 20. The multiple lines and good spatial coverage make this source suitable for a multiplexed wavelength solution for NIRSPEC in sparse aperture mode. In the mid-infrared, this region constitutes a very good target for both wavelength solution and, for the slit mode, spectral trace, the latter thanks to the irregularities in the luminosity distribution which make it possible to trace the emission of individual knots. For NIRSPEC, star-forming regions such as Orion Peak 1 are similar to reflection nebulae in terms of usefulness as calibration sources; star-forming regions may have higher line-to-continuum contrast and more lines, but more sparse and irregular spatial coverage

**Table 6.** Summary of line and continuum fluxes for selected targets

Target	Wavelength ( $\mu$ m)	Area	Line flux (erg/s/cm <sup>2</sup> )	Continuum flux (Jy)
$\gamma$ Cas	3.039	Point source	3.73e-11	80
$\gamma$ Cas	7.460	Point source	1.58e-11	28
Cas A FMK 1	1.028	Unresolved?	1.28e-12	--
NGC 1333	2.12183	45"x4.5" region	4.8e-14	2.7e-3 (estimated)
NGC 6543 S knot	1.9446	1"x3.5"	8.0e-14	--
Orion Peak 1	3.8464	14"x20"	1.0e-11	8
Orion Peak 1	8.991	14"x20"	6.2e-11	35
Orion Peak 1	18.713	14"x27"	3.24e-10	1300

## 4.0 Conclusions

A variety of astronomical sources could be useful for the calibration of the spectrographs on JWST. We have considered a few examples of possible calibrators, chosen among bright, well-studied sources; selected measurements of line and continuum fluxes are reported in Table 6. We have estimated their usefulness as calibrators on the basis of their gross properties: simulated images and spectra would be necessary for a more thorough assessment of the benefits and pitfalls of using astronomical targets as line calibrators. We have focused on wavelength solution, wavelength zero point, spectral trace, and line-spread function.

Emission-line (Be) stars are good targets for single-aperture wavelength solution, wavelength zero point, and line-spread function. The case we considered,  $\gamma$  Cas, is too bright for JWST, and the lines are intrinsically too broad to obtain a reliable LSF at  $R \sim 1000$ ; however, it should be easy to find a fainter Be star with narrower lines. These

targets do not allow any multiplexing; only a single aperture (or location along the slit for MIRI) can be calibrated at a time.

Supernova remnants such as Cas A, with discrete knots of line emission, are probably less useful as line calibrators. However, other supernova remnants may have extended line emission, and their large angular size would make them suitable calibration sources for JWST.

Reflection nebulae have strong, diffuse line emission in fluorescent lines of  $H_2$ , and can exceed  $5'$  in diameter. However, typical line-to-continuum ratios are only a few, which means that a sparse aperture pattern with non-overlapping spectra must be employed. The lines are narrow and well-defined, and therefore can be used to verify the validity of the wavelength solution in NIRSPEC with exposure times of a few tens of seconds per aperture pattern. However, since only sparse aperture patterns can be employed, a complete calibration of all apertures is not feasible. The nebula we consider, NGC 1333, does not appear to have useful emission features for MIRI calibration.

Star-forming regions, such as Orion Peak 1, are similar to reflection nebulae for the purpose of NIRSPEC calibration. They have somewhat larger line-to-continuum ratios, and the exposure times are similar; however, the continuum remains too strong to allow the use of dense aperture patterns. Their size is smaller and emission less regular, so reflection nebulae are probably preferable for NIRSPEC calibration. Nevertheless, Orion Peak 1 has very useful spectral features for MIRI calibration.

Finally, planetary nebulae have very low continuum emission (excluding the central star) and therefore can be used as calibration sources in dense aperture mode, with a judicious choice of filter and aperture pattern to avoid strong line overlap. Exposure times of a few tens of seconds are sufficient. The emission is spatially irregular and, while extended, does not normally cover areas as large as reflection nebulae; thus their efficiency as dense aperture mode calibrators is somewhat reduced. Simulations of the observations of extended planetary nebulae in dense aperture mode should be carried out to assess their practical usefulness; in principle, however, such calibrations are feasible.

In summary, astronomical sources suitable to support the calibration of JWST spectrographs exist, and many can be observed with good S/N with typical exposure times of a few tens of seconds. The viability of a calibration program based on astronomical sources depends primarily on the degree of stability and modelability of JWST instruments. For example, if the wavelength zero point is constant through a slew of several degrees, then known line sources can be used for the wavelength calibration; on the other hand, if a wavelength zero point calibration is required frequently, an external source would be inefficient. For other calibrations, such as wavelength solution and dispersion, modelability is very important; if every aperture needs an independent wavelength solution, the lower efficiency of astronomical sources compared to on-board lamps must be taken into account. Considering that lamp-based line calibrations do not constitute a large fraction of the overall calibration budget for JWST (Henry and Casertano 2002), a loss of efficiency by a factor of a few should not impact significantly the total cost of the JWST calibration program. However, the use of external calibration sources does increase significantly the complexity of calibration planning and analysis, and therefore may constitute an addi-

tional cost in JWST operations that could be alleviated if on-board calibration sources were available.

An important consideration is the frequency of viable calibration sources in the sky. Some, such as reflection and planetary nebulae, are very common - with hundreds of catalogued objects, so that a suitable target is likely to be accessible at any time. Star-forming regions are less common and their properties more varied; therefore a significant effort will be needed to select and screen a set of suitably placed sources with the properties required to be used as JWST calibration sources.

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