THE ASTROPHYSICAL JOURNAL, 487:962–966, 1997 October 1
© 1997. The American Astronomical Society. All rights reserved. Printed in U.S.A.

NEW WAVELENGTH DETERMINATIONS OF MID-INFRARED FINE-STRUCTURE LINES BY *INFRARED SPACE OBSERVATORY* SHORT WAVELENGTH SPECTROMETER[1]

H. FEUCHTGRUBER,[2] D. LUTZ,[2] D. A. BEINTEMA,[3,4] E. A. VALENTIJN,[3,4,5] O. H. BAUER,[2]
D. R. BOXHOORN,[3,4] TH. DE GRAAUW,[4,5] L. N. HASER,[2] G. HAERENDEL,[2] A. M. HERAS,[3]
R. O. KATTERLOHER,[2] D. J. M. KESTER,[4] F. LAHUIS,[3,4] K. J. LEECH,[3] P. W. MORRIS,[3,4]
P. R. ROELFSEMA,[3,4] A. SALAMA,[3] S. G. SCHAEIDT,[2,3] H. W. W. SPOON,[2]
B. VANDENBUSSCHE,[3,6] AND E. WIEPRECHT[2,3]
Received 1997 February 5; accepted 1997 May 2

ABSTRACT

We report accurate new wavelengths for 29 mid-infrared ionic fine-structure lines, based on observations with the Short Wavelength Spectrometer (SWS) on board the *Infrared Space Observatory* (*ISO*). Our results originate from observations of NGC 7027, NGC 6543, NGC 6302, the Circinus galaxy, Sgr A West, and W51 IRS 2. The obtained accuracies ($\lambda/\Delta\lambda$) range from 3×10^4 to 1×10^5, depending on instrumental mode and uncertainty in radial velocities.

Subject headings: atomic data — infrared: ISM: lines and bands — line: identification — planetary

1. INTRODUCTION

The Short Wavelength Spectrometer (SWS; de Graauw et al. 1996) on board ESA's cryogenic *Infrared Space Observatory* (*ISO*; Kessler et al. 1996) has been in operation since 1995 December. Its high sensitivity and full coverage of the wavelength range 2.4–45 μm allow spectroscopy of transitions that were unobservable from ground-based or airborne telescopes. As accurate wavelengths from laboratory or astronomical measurements were previously unavailable for many fine-structure transitions of highly ionized species, the SWS Instrument Dedicated Team has initiated an effort to quickly provide improved wavelengths for lines that may be of relevance in a variety of sources being observed with *ISO* SWS. We make use of observations obtained with both the SWS grating spectrometer (resolving power $R \sim 1000$–2000) and the SWS Fabry-Perot (FP) interferometer with resolving power $R \sim 30{,}000$.

The absolute wavelength calibration of the SWS grating section established during the performance verification (PV) phase of *ISO* has an uncertainty of 0.5–1.0 steps of the grating scanner (Valentijn et al. 1996). This value in instrumental units can be translated into the actual wavelength uncertainty for every spectral line and typically corresponds to $\lambda/\Delta\lambda = 1 \times 10^4$. These numbers represent the intrinsic accuracy of the grating wavelength calibration as obtained from a large set of observations in PV. The wavelength accuracy of an *individual* SWS grating observation may, however, be affected by the pointing accuracy of the satellite and the structure of the target, which can cause apparent wavelength shifts up to 100 km s^{-1} due to offsets between center of slit and actual source position. This is about 3 times as large as the instrumental accuracy. In order to take full advantage of the excellent intrinsic accuracy, we have employed a scheme where in the same observation other accurately known lines are used for reference (see § 2 for details). This procedure also accounts for uncertainties in the source velocity.

The absolute Fabry-Perot wavelength accuracy is 2 FP steps in the range 11.4–26.0 μm and 1 FP step for the wavelength range above 26 μm, corresponding to individual errors of the spectral lines of typically $\lambda/\Delta\lambda = 1 \times 10^5$. Pointing effects on the FP wavelength determinations are negligible. Slight mispointings cause a detuning of the order-sorting grating profile with respect to the FP transmission, which translates into a loss of a few percent of flux, but no measurable wavelength shift. No spectral ghosts have been identified in SWS spectra, which could lead to misidentifications of the lines. The FP wavelength calibration has proven to be stable on a timescale of more than 1 yr, while the grating wavelength calibration shows a slight time-dependent shift. This effect is, however, neglected here as it is smaller than 0.1 grating scanner step per month, and all new wavelengths reported here were determined from observations close to the actual calibration during PV. In addition, note that a shift that is constant for the whole scanner range will be absorbed by the reference line procedure.

2. OBSERVATIONS AND DATA REDUCTION

We have analyzed observations of the planetary nebulae NGC 6543, NGC 7027, and the Circinus galaxy made during PV and observations of NGC 6302, Sgr A West, and W51 IRS 2 from various guaranteed time proposals. This paper exclusively focuses on wavelength determinations; detailed discussions of the sources are presented elsewhere. Note that only those observed lines for which we could improve the wavelengths are mentioned here. Lines with accurately known wavelengths, including most of the reference lines, were measured on several other targets for wavelength calibration purposes (Valentijn et al. 1996). Our observations include scanning Fabry-Perot line observations (AOT SWS07), grating line observations (AOT

[1] Based on observations made with *ISO*, an ESA project with instruments funded by ESA Member States (especially the PI countries: France, Germany, The Netherlands, and the United Kingdom) and with the participation of ISAS and NASA. The SWS is a joint project of SRON and MPE.

[2] Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany.

[3] *ISO* Science Operations Centre, Astrophysics Division of ESA, Villafranca, P.O. Box 50727, E-28080, Madrid, Spain.

[4] Space Research Organisation of the Netherlands and Kapteyn Institute, P.O. Box 800, 9700 AV Groningen, The Netherlands.

[5] Kapteyn Astronomical Institute, P.O. Box 800, 9700 AV Groningen, The Netherlands; fgb@isow37.vilspa.esa.es.

[6] Institute for Astronomy, University of Leuven, B-3001 Heverlee, Belgium.

SWS02), and low-resolution full grating scans (AOT SWS01). The different spectral and spatial resolutions for these modes are described by de Graauw et al. (1996). The data reduction of all measurements was done using the SWS Interactive Analysis software package. Gaussian fits to the spectral lines provided the center wavelengths, which first were corrected for the sum of heliocentric and the mean *ISO* radial velocity shift. Typical changes of the later shift during the observations reported here are on the order of 0.2–0.3 km s^{-1}; deviations from the mean value were therefore neglected.

2.1. *Use of Reference Lines*

The resulting center wavelengths are corrected further to consider velocity errors. For that purpose, we determine offsets between observed and predicted wavelengths for simultaneously observed reference lines with well-known rest wavelengths. In the case of grating observations, the velocity error may have a pointing-induced component. Since SWS has three different apertures that are used in sequence, we require that reference wavelengths for a particular line have to be taken from observations using the same SWS aperture, i.e., the same pointing. This is because SWS observations with different apertures constitute independent pointings, so that the *ISO* blind pointing accuracy of about 3″.5 (Kessler et al. 1996) may have to be considered. Pointing effects are, however, negligible within a single aperture observation since the short-term pointing jitter is much smaller (about 0″.5). In some cases, there are apparent small velocity differences even between different lines on the same source. Since it is well known that in sources like the Circinus galaxy there exist velocity shifts between high- and low-excitation lines (Oliva et al. 1994), we have tried to account for this by using reference lines with excitation potential close to the one of the line to be determined.

While wavelengths of narrow lines measured with the FP are to the first order not affected by pointing errors, an additional uncertainty of 1 km s^{-1} is included in the error estimates to account for spatial variations of the velocity across the source, which are a potential problem at the spectral resolving power of the FP even for sources like planetary nebulae. The SWS slit sizes, however, are larger than or equal to 14″ × 20″ depending on the slit used and therefore give a good average of the intrinsic source velocities of the selected targets. For example, our prime target NGC 7027 is smaller than our aperture, and NGC 6543 is only slightly larger than the small dimension of the slit. Our basic assumption is that if the centers of gravity of the velocity profiles for different species agree within the quoted uncertainty, a detailed match of spatial or velocity structure is not required. This assumption is supported by the FP wavelength calibration procedure and its verification (Valentijn et al. 1996). The agreement between the calibration derived from calibration sources internal to SWS and verification on lines with accurately known wavelengths in astronomical sources is excellent for a variety of sources, including some planetary nebulae.

In several cases, we had detections on more than one target; here we selected the observations with the best signal-to-noise ratio (S/N) and the best reference wavelength frames. The new wavelength determinations together with some other line properties can be found in Table 1. The framework of fine-structure reference lines that were used for the individual observations of our targets is listed in Table 2. The offset listed in Table 2 gives, for a particular observation, the difference between observed and literature wavenumber of the reference line. Apart from literature wavenumbers, Table 2 also includes rest wavenumbers that were determined during independent observations by the SWS grating or FP on other targets. "SWS error" denotes the measurement uncertainty in the SWS observation of the reference line. Together with the uncertainty of the literature wavenumber, it is propagated into the error of new wavelength determinations that are tied to this line.

2.2. *NGC 7027*

A full SWS grating scan at reduced resolution ($\approx$maximum resolution/2) from 2.36 to 45.2 μm and grating line scans at many wavelengths provided a large number of line detections in this high-excitation planetary nebula (Beintema et al. 1996). FP observations on nine spectral lines were carried out. Table 1 includes all line observations where the wavelength accuracy could be improved. The fine-structure reference lines can be found in Table 2; in addition, we included hydrogen recombination lines as references.

No significant deviations between observed and predicted wavelengths were detected for the reference lines in all three applied SWS observing modes, adopting the heliocentric velocity $+8.8 \pm 0.6$ km s^{-1} from Schneider et al. (1983). Hyperfine splitting of the [Na IV] line has been reported by Kelly & Lacy (1995). Because of the lower spectral resolution of the SWS, it was not possible to resolve the hyperfine components, but the center wavelength we determined is in perfect agreement with their results.

2.3. *NGC 6543*

Wavelengths for the ionic lines from [S III] at 33.48 μm and [Ar III] at 21.83 μm are provided by the observations on the low-excitation planetary nebula NGC 6543 (Beintema et al. 1996). All other observed lines were already detected in NGC 7027 with a better S/N.

The grating observations on NGC 6543 are in excellent agreement with the reference lines adopting the heliocentric velocity -66.1 ± 0.4 km s^{-1} (Schneider et al. 1983); therefore, no shift had to be applied to the [Ar III] 21.83 μm line. For the [S III] 18.71 μm line observed by the FP, we get a wavenumber of 534.399 ± 0.006 cm^{-1}, differing slightly ($<2\ \sigma$) from that reported by Kelly & Lacy (1995). Our value has a slightly higher error but agrees better with previous observations by Moorwood et al. (1978, 1980).

2.4. *NGC 6302*

This extremely high excitation planetary nebula is a unique source of infrared fine-structure lines (Pottasch et al. 1985, 1996; Ashley & Hyland 1988; Reconditi & Oliva 1993) One low-resolution full grating scan from 2.36 to 45.3 μm added new rest wavelengths for transitions of K, Na, Mg, and Si ions at high-ionization energies. The seven fine-structure reference lines listed in Table 2 provide the information on pointing and velocity errors. For wavelengths below 5 μm, hydrogen recombination lines are available as additional references and fit the reference frame deduced from the fine-structure lines.

The observed lines in NGC 6302 had to be shifted on average by 35 km s^{-1} with respect to the heliocentric velocity of -39 ± 2 km s^{-1} given by Acker et al. (1992), prob-

TABLE 1

SUMMARY OF NEW WAVELENGTH DETERMINATIONS

Ion	Transition (u–l)	Vacuum Wavelength[a] (μm)	Rest Wavenumber[a] (cm^{-1})	χ_{lower} (eV)	χ_{upper} (eV)	Observation Date	Target
[Si IX]	$^3P_2$–$^3P_1$	2.58423 ± (23)	3869.63 ± (33)	303.17	351.10	1996 Jan 28[b]	Circinus
[Al V]	$^2P_{1/2}$–$^2P_{3/2}$	2.90519 ± (37)	3442.12 ± (43)	120.0	153.83	1995 Dec 11[c]	NGC 7027
[K VII]	$^3P_{3/2}$–$^2P_{1/2}$	3.19053 ± (15)	3134.28 ± (14)	99.4	117.56	1996 Feb 18[c]	NGC 6302
[Ca IV]	$^2P_{1/2}$–$^2P_{3/2}$	3.20671 ± (15)	3118.46 ± (14)	50.91	67.27	1995 Dec 11[c]	NGC 7027
[Mg IV]	$^2P_{1/2}$–$^2P_{3/2}$	4.48668 ± (30)	2228.82 ± (15)	80.14	109.24	1995 Dec 19[b]	NGC 7027
[Ar VI]	$^2P_{3/2}$–$^2P_{1/2}$	4.52952 ± (31)	2207.74 ± (15)	75.02	91.01	1995 Dec 19 [b]	NGC 7027
[K III]	$^2P_{1/2}$–$^2P_{3/2}$	4.61802 ± (47)	2165.43 ± (22)	31.63	45.80	1995 Dec 11[c]	NGC 7027
[Na VII]	$^2P_{3/2}$–$^2P_{1/2}$	4.68472 ± (33)	2134.60 ± (15)	172.15	208.44	1996 Feb 18[c]	NGC 6302
[Mg VII].....	$^3P_2$–$^3P_1$	5.5032 ± (12)	1817.10 ± (41)	186.51	224.95	1996 Feb 18[c]	NGC 6302
[Mg V]	$^3P_1$–$^3P_2$	5.60985 ± (63)	1782.58 ± (20)	109.24	141.27	1995 Dec 19[b]	NGC 7027
[K IV]	$^3P_1$–$^3P_2$	5.9820 ± (12)	1671.68 ± (35)	45.80	60.91	1995 Dec 11[c]	NGC 7027
[Si VII]	$^3P_0$–$^3P_1$	6.4922 ± (11)	1540.29 ± (25)	205.05	246.52	1996 Feb 18[c]	NGC 6302
[Na III].....	$^2P_{1/2}$–$^2P_{3/2}$	7.3177 ± (12)	1366.54 ± (23)	47.29	71.62	1995 Dec 11[c]	NGC 7027
[Ne VI]	$^2P_{3/2}$–$^2P_{1/2}$	7.6524 ± (12)	1306.78 ± (21)	126.21	157.93	1995 Dec 11[c]	NGC 7027
[Fe VII].....	$^3F_4$–$^3F_3$	7.8145 ± (12)	1279.67 ± (20)	99.1	124.98	1995 Dec 11[c]	NGC 7027
[Na VI].....	$^3P_2$–$^3P_1$	8.61059 ± (88)	1161.36 ± (12)	138.39	172.15	1996 Feb 18[c]	NGC 6302
[Fe VII].....	$^3F_3$–$^3F_2$	9.5267 ± (11)	1049.68 ± (12)	99.1	124.98	1995 Dec 11[c]	NGC 7027
[Ar V]	$^3P_1$–$^3P_0$	13.1022 ± (2)	763.231 ± (11)	59.81	75.02	1995 Dec 31[d]	NGC 7027
[Mg V]	$^3P_0$–$^3P_1$	13.5213 ± (2)	739.576 ± (11)	109.24	141.27	1995 Dec 31[d]	NGC 7027
[Ne V].....	$^3P_2$–$^3P_1$	14.3217 ± (2)	698.242 ± (10)	97.12	126.21	1995 Dec 31[d]	NGC 7027
[Na VI].....	$^3P_1$–$^3P_0$	14.3964 ± (21)	694.62 ± (10)	138.39	172.15	1996 Feb 18[c]	NGC 6302
[Ne III]	$^3P_1$–$^3P_2$	15.5551 ± (3)	642.878 ± (9)	40.96	63.45	1995 Dec 31[d]	NGC 7027
[Ar III]	$^3P_0$–$^3P_1$	21.8293 ± (20)	458.10 ± (4)	27.63	40.74	1995 Dec 23[b]	NGC 6543
[Ne V].....	$^3P_1$–$^3P_0$	24.3175 ± (3)	411.226 ± (6)	97.12	126.21	1995 Dec 31[d]	NGC 7027
[O IV]	$^2P_{3/2}$–$^2P_{1/2}$	25.8903 ± (3)	386.245 ± (5)	54.93	77.41	1995 Dec 31[d]	NGC 7027
[Fe III]	$^5D_2$–$^5D_3$	33.0384 ± (66)	302.678 ± (60)	16.19	30.65	1996 Feb 19[c]	Sgr A West
[S III]	$^3P_1$–$^3P_0$	33.4810 ± (3)	298.677 ± (3)	23.34	34.79	1996 Jan 27[d]	NGC 6543
[Si II]	$^2P_{3/2}$–$^2P_{1/2}$	34.8152 ± (5)	287.231 ± (5)	8.15	16.35	1996 May 9[d]	W51 IRS2
[Ne III]	$^3P_0$–$^3P_1$	36.0135 ± (3)	277.674 ± (3)	40.96	63.45	1996 Jan 27[d]	NGC 6543

NOTE.—χ_{lower} and χ_{upper} denote excitation and ionization potentials.

[a] Numbers in brackets give errors on last decimals.

[b] Grating line scan.

[c] Full low-resolution grating scan.

[d] Fabry-Perot line scan.

ably because of a pointing error. The error of the [Si VII] 6.49 μm line is larger because the line is weak. We find the rest wavelengths for the reference lines [Si VII] at 2.48 μm and [Mg VIII] 3.028 μm at somewhat longer wavelengths than Reconditi & Oliva (1993) but still consistent within the errors. The other reference lines match well, however, and there is no reason to expect large velocity differences between ions of different ionization energies within this planetary nebula.

It should be noted that we do not detect the 9 μm [Mg VII] line that was found at 9.009 μm by Kelly & Lacy (1995) in NGC 7027. The presence of the strong 5.5 μm [Mg VII] line, however, indicates that this ion is present, and a strong 9.009 μm line would be expected for the density and electron temperature of NGC 6302. Since it is unlikely that the [Mg VII] atomic data are wrong by the large factor required to suppress the 9.009 μm line, it appears that the weak feature detected by Kelly & Lacy (1995) is not due to [Mg VII]. This is supported by the fact that the [Mg VII] 5.5 μm line was not detected by SWS in NGC 7027, which is of lower excitation than NGC 6302. Likely the 9 μm [Mg VII] line in NGC 6302 is blended with [Ar III] 8.991 μm at the SWS spectral resolving power of 2000.

We attribute the lines at 8.61 and 14.39 μm to [Na VI]. The presence of both lower and higher ionized sodium, [Na III], [Na IV] and [Na VII], supports this identification. At first glance, the identification of the line at 3.19 μm with [K VII] could be questioned because of the nondetection in NGC 6302 of lower ionization stages of potassium. Lines of [K III] and [K IV] were detected in the lower excitation planetary NGC 7027. We have run a simplified photoionization model using CLOUDY (Ferland 1993), which reproduced the NGC 6302 neon line fluxes of various ionization stages. However, this model predicts the [K VII] line to be the brightest of the [K III] to [K VII] series of ionic lines. The measured upper limits for the lower excitation [K] lines in the SWS spectrum of NGC 6302 are consistent with the flux values of the model predictions.

2.5. *Circinus Galaxy*

The rich SWS spectrum of this Seyfert galaxy is discussed by Moorwood et al. (1996). A better rest wavelength can be determined for the 2.58 μm line of [Si IX]. A somewhat complex reference procedure had to be used because different species may have different intrinsic velocities. The accuracy is determined by excluding first-differential pointing errors between apertures 1 and 2 using the [Ne V] 14.3 and 24.3 μm lines. Both lines show the same shift of 51 km s^{-1}. Having excluded such a differential pointing error, it is best to use the [Si IX] 3.94 μm line as a reference for the 2.58 μm line, in order to avoid possible velocity shifts between lines from the narrow-line region and coronal lines. The shift of the [Si IX] 3.94 μm line with respect to the observation of Oliva et al. (1994) is 33 km s^{-1}. Therefore, the lines in Table 1 include a shift by this velocity and a correction for the heliocentric velocity of 439 ± 2 km s^{-1} (Freeman et al. 1977). A similar shift found for the other reference lines [Ar III] and [S III] gives confidence that we can propagate

TABLE 2

SUMMARY OF REFERENCE WAVENUMBERS

Observation Date	Target	Ion	Transition (u–l)	Reference Wavenumber (cm^{-1})	Offset (cm^{-1})	SWS Error (cm^{-1})	Reference
1995 Dec 11[b]	NGC 7027	[Ar II]	$^2P_{1/2}$–$^2P_{3/2}$	1431.5831 ± 0.0007	0.03	0.25	Yamada, Kanamori, & Hirota 1985
1995 Dec 11[b]	NGC 7027	[Ar V]	$^3P_2$–$^3P_1$	1265.57 ± 0.04	−0.01	0.20	Kelly & Lacy 1995
1995 Dec 19[a]	NGC 7027	[Ar II]	$^2P_{1/2}$–$^2P_{3/2}$	1431.5831 ± 0.0007	0.02	0.13	Yamada et al. 1985
1995 Dec 19[a]	NGC 7027	[Ar III]	$^3P_1$–$^3P_2$	1112.176 ± 0.015	−0.05	0.07	Kelly & Lacy 1995
1995 Dec 19[a]	NGC 7027	[Na IV]	$^3P_1$–$^3P_2$	Hyperfine splitting	...	0.07	Kelly & Lacy 1995
1995 Dec 19[a]	NGC 7027	[S IV]	$^2P_{3/2}$–$^2P_{1/2}$	951.430 ± 0.01	0.02	0.05	E. Serabyn 1991, private communication
1995 Dec 31[c]	NGC 7027	[Ne II]	$^2P_{1/2}$–$^2P_{3/2}$	780.424 ± 0.001	0.002	0.012	Yamada et al. 1985
1995 Dec 31[c]	NGC 7027	[S III]	$^3P_2$–$^3P_1$	534.387 ± 0.005	0.01	0.015	Kelly & Lacy 1995
1995 Dec 23[a]	NGC 6543	[Ar III]	$^3P_1$–$^3P_2$	1112.176 ± 0.015	−0.05	0.07	Kelly & Lacy 1995
1995 Dec 23[a]	NGC 6543	[S III]	$^3P_2$–$^3P_1$	534.387 ± 0.005	0.02	0.03	Kelly & Lacy 1995
1996 Mar 22[c]	NGC 6543	[S III]	$^3P_2$–$^3P_1$	534.387 ± 0.005	0.012	0.006	Kelly & Lacy 1995
1996 Feb 18[b]	NGC 6302	[Si VII]	$^3P_1$–$^3P_2$	4026.84 ± 0.20	−0.54	0.48	Reconditi & Oliva 1993
1996 Feb 18[b]	NGC 6302	[Mg VIII]	$^2P_{3/2}$–$^2P_{1/2}$	3302.56 ± 0.27	−0.62	0.38	Reconditi & Oliva 1993
1996 Feb 18[b]	NGC 6302	[Ar VI]	$^3P_{3/2}$–$^2P_{1/2}$	2207.74 ± 0.15	−0.05	0.29	Table 1 (NGC 7027)
1996 Feb 18[b]	NGC 6302	[Ar II]	$^2P_{1/2}$–$^2P_{3/2}$	1431.5831 ± 0.0007	0.04	0.25	Yamada et al. 1985
1996 Feb 18[b]	NGC 6302	[Ne VI]	$^2P_{3/2}$–$^2P_{1/2}$	1306.78 ± 0.21	0.02	0.21	Table 1 (NGC 7027)
1996 Feb 18[b]	NGC 6302	[Ar III]	$^3P_1$–$^3P_2$	1112.176 ± 0.015	−0.03	0.07	Kelly & Lacy 1995
1996 Feb 18[b]	NGC 6302	[Ne V]	$^3P_2$–$^3P_1$	698.242 ± 0.01	0.02	0.10	Table 1 (NGC 7027)
1996 Jan 28[a]	Circinus	[Si IX]	$^3P_1$–$^3P_0$	2540.84 ± 0.25	0.00	0.20	Oliva et al. 1994
1996 Jan 28[a]	Circinus	[Ar III]	$^3P_1$–$^3P_2$	1112.176 ± 0.015	−0.02	0.07	Kelly & Lacy 1995
1996 Jan 28[a]	Circinus	[Ne V]	$^3P_2$–$^3P_1$	698.242 ± 0.010	0.05	0.05	Table 1 (NGC 7027)
1996 Jan 28[a]	Circinus	[S III]	$^3P_2$–$^3P_1$	534.387 ± 0.005	0.00	0.03	Kelly & Lacy 1995
1996 Jan 28[a]	Circinus	[Ne V]	$^3P_1$–$^3P_0$	411.226 ± 0.006	0.02	0.04	Table 1 (NGC 7027)
1996 Feb 19[b]	Sgr A West	[S III]	$^3P_2$–$^3P_1$	534.387 ± 0.005	−0.016	0.06	Kelly & Lacy 1995
1996 Feb 19[b]	Sgr A West	[Fe III]	$^5D_3$–$^5D_4$	436.205 ± 0.038	0.04	0.08	Erickson et al. 1989
1996 Feb 19[b]	Sgr A West	[S III]	$^3P_1$–$^3P_0$	298.677 ± 0.003	0.007	0.016	Table 1 (NGC 6543)
1996 May 9[c]	W51 IRS2	[Ne II]	$^2P_{1/2}$–$^2P_{3/2}$	780.424 ± 0.001	−0.005	0.012	Yamada et al. 1985
1996 May 9[c]	W51 IRS2	[Ne III]	$^3P_1$–$^3P_2$	642.878 ± 0.009	−0.005	0.009	Table 1 (NGC 7027)
1996 May 9[c]	W51 IRS2	[S III]	$^3P_1$–$^3P_0$	298.677 ± 0.003	0.002	0.003	Table 1 (NGC 6543)
1996 May 9[c]	W51 IRS2	[Ne III]	$^3P_0$–$^3P_1$	277.674 ± 0.003	0.000	0.003	Table 1 (NGC 6543)

NOTE.—See § 2 for explanations.

[a] Grating line scan.

[b] Full low-resolution grating scan.

[c] Fabry-Perot line scan.

the error of the 3.94 μm line together with an additional uncertainty of 10 km s^{-1} into the error of the 2.58 μm transition.

2.6. *Sgr A West*

For our observation of Sgr A West, the SWS slit centers were located at the position of the radio source Sgr A*. The full low-resolution grating scan on this target (Lutz et al. 1996) provides a new rest wavelength for the [Fe III] transition at 33.038 μm. Out of the many lines detected on this target, we have chosen the [S III] 18.71, 33.48 μm lines together with the [Fe III] 22.925 μm line as reference frame. Special care has to be taken in deducing a rest wavelength from an observation of this region, since the spatial and velocity structure are complex. Also, the distribution of [Fe III] emission is different from other low-ionization lines (Lutz, Krabbe, & Genzel 1993; Lacy, Achtermann, & Serabyn 1991). To account for these effects, we have adopted a two-step reference line procedure. First, measurements of the [S III] 18.71 μm and [Fe III] 22.925 μm lines were analyzed to determine the apparent velocity offset between the [S III] and [Fe III] emitting media: the [Fe III] emission was found to be offset by 36 km s^{-1}. These two lines have rest wavelengths determined from non-*ISO* abbreviations and are observed with the same pointing. Second, the [S III] 33.48 μm line was used in the standard manner as a reference line for the pointing in which also the [Fe III] 22.925 μm line is observed, and the offset [Fe III]/[S III] determined in the first step was applied on top. Our total error estimate includes measurement uncertainties, uncertainties in the three reference wavelengths involved, and an additional 30 km s^{-1} uncertainty we have introduced since the [Fe III]/[S III] offset may differ somewhat for the two apertures involved that are not identical in size.

2.7. *W51 IRS 2*

This Fabry-Perot observation centered on the W51 IRS 2 H II region was carried out to improve the rest wavelength of the [Si II] 34.8 μm line. Instead of applying a heliocentric correction for this target, we directly used the four reference lines from [Ne II], [Ne III], and [S III] observed with the FP to provide a consistent velocity frame.

3. CONCLUSIONS

The *ISO* Short Wavelength Spectrometer has been used to obtain new rest wavelengths for mid-infrared fine-structure lines. For high-excitation lines, in particular, the accuracy achieved significantly improves previous values that were frequently based on energy level differences reconstructed from UV/optical spectroscopy; these differences were of similar sized large numbers and hence were intrinsically inaccurate. The new wavelengths should be useful for a wide range of mid-infrared spectroscopic studies.

This work was supported by DARA grants 50 QI9402 3 and 50 QI 8610 8. The SWS acknowledges contributions from KU Leuven, Steward Observatory, and Phillips Laboratory.

REFERENCES

Acker, A., Ochsenbein, F., Stenholm, B., Tylenda, R., Marcout, J., & Schohn, C. 1992, Strasbourg-ESO Catalogue of Galactic Planetary Nebulae (Garching: ESO)
Ashley, M. C. B., & Hyland, A. R. 1988, ApJ, 331, 532
Beintema, D. A., et al. 1996, A&A, 315, L253
de Graauw, Th., et al. 1996, A&A, 315, L49
Erickson, E. F., Haas, M. R., Simpson, J. P., Rubin, R., & Colgan, S. 1989, BAAS, 21, 1156
Ferland G. J. 1993, Hazy: A Brief Introduction to CLOUDY, Univ. Kentucky, Dept. Phys. Astron. Int. Rep.
Freeman, K. C., Karlsson, B., Lynga, G., Burrell, J. F., van Woerden, H., Goss, W. M., & Mebold, U. 1977, A&A, 55, 445
Kelly, D. M., & Lacy, J. H. 1995, ApJ, 454, L161
Kessler, M. F. K., et al. 1996, A&A, 315, L27
Lacy, J. H., Achtermann, J. M., & Serabyn E. 1991, ApJ, 380, L71
Lutz, D., Krabbe, A., & Genzel, R. 1993, ApJ, 418, 244
Lutz, D., et al. 1996, A&A, 315, L269
Moorwood, A. F. M., Baluteau, J.-P., Anderegg, M., Coron, N., & Biraud, Y. 1978, ApJ, 224, 101
Moorwood, A. F. M., Baluteau, J.-P., Anderegg, M., Coron, N., Biraud, Y., & Fitton B. 1980, ApJ, 238, 565
Moorwood, A. F. M., et al. 1996, A&A, 315, L109
Oliva, E., Salvati, M., Moorwood, A. F. M., & Marconi, A. 1994, A&A, 288, 457
Pottasch, S. R., Beintema, D., Dominguez-Rodriguez, F. J., Schaeidt, S., Valentijn, E., & Vandenbussche, B. 1996, A&A, 315, L261
Pottasch, S. R., Preite-Martinez, A., Olnon, F. M., Raimond, E., Beintema, D. A., & Habing, H. J. 1985, A&A, 143, L11
Reconditi, M., & Oliva E. 1993, A&A, 274, 662
Schneider, S. E., Terzian, Y., Purgathofer, A., & Perinotto, M. 1983, ApJS, 52, 399
Valentijn, E. A., et al. 1996, A&A, 315, L60
Yamada, C., Kanamori, H., & Hirota, E. 1985, J. Chem. Phys., 83, 552