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SWS observations of the Galactic center *

D. Lutz[1], H. Feuchtgruber[1,2], R. Genzel[1], D. Kunze[1], D. Rigopoulou[1], H.W.W. Spoon[1], C.M. Wright[1], E. Egami[1], R. Katterloher[1], E. Sturm[1], E. Wieprecht[1], A. Sternberg[3], A.F.M. Moorwood[4], and Th. de Graauw[5]

[1] Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
[2] ISO Science Operations Center, Astrophysics Division of ESA, P.O. Box 50727, E-28080 Villafranca/Madrid, Spain
[3] School of Physics and Astronomy and The Wise Observatory, Tel Aviv University, Tel Aviv 69978, Israel
[4] European Southern Observatory, Karl-Schwarzschildstraße 2, D-85748 Garching, Germany
[5] Space Research Organization of the Netherlands and Kapteyn Institute, P.O. Box 800, 9700 AV Groningen, The Netherlands

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Abstract. We present a 2.4–45 μm spectrum of the center of our Galaxy obtained with the Short Wavelength Spectrometer (SWS) on board ISO. The wide range of ionic fine structure lines observed yields an average effective temperature for the ionizing stars of 35000 K, with a small contribution of significantly hotter stars, consistent with ageing of an active period of massive star formation that took place a few million years ago. Several absorption features from the foreground cold ISM are detected for the first time. The extinction law towards the Galactic center lacks the expected deep minimum in the 4–8 μm range. From the detection of OH 34.6 μm absorption, we infer that radiative pumping is likely the major excitation mechanism for OH emission from the Galactic center. We discuss the rich spectrum of iron and nickel and conclude that the [Fe II] spectrum is inconsistent with pure collisional excitation. This calls for caution in interpretation of [Fe II] emission in sources, such as starburst galaxies, which contain intense radiation fields.

Key words: Galaxy: center – ISM: general – dust: extinction – Infrared: ISM: lines and bands

1. Observations

A 2.4–45 μm spectrum of the Galactic center was obtained with ISO-SWS on Feb. 19, 1996. The slowest version of the fullscan observing mode (SWS01, de Graauw 1996) was used. For an extended source like the galactic center, the wavelenght dependent spectral resolving power will be slightly less than the values between about 700 and 2000 which are found for a compact source observed in SWS01 mode. The spectrum was reduced with the SWS interactive analysis system (IA), using calibration files as of June 25 and additional tools to improve flatfielding and to remove fringes.

The aperture was centered on Sgr A*, with the long axis oriented at position angle -1.4°. The $14'' \times 20''$ aperture for the short wavelengths also included some of the well-known mid-infrared sources like IRS3 and IRS1, much of the ionized 'bar' including the 'mini-cavity' region, and part of the ionized northern arm. For longer wavelengths, more of the ionized mini-spiral is covered by the larger ($20''\times33''$) aperture. We did not attempt to correct for this in the spectrum displayed in Fig. 1, leading to jumps in the spectrum where the aperture size changes. The aperture size was however taken into account by dividing by 2 all fluxes for lines beyond 30 μm when interpreting line ratios.

2. Ionizing continuum and stellar population

The detection of fine structure lines of [Ne II], [Ne III], [S III], [S IV], [Ar II], [Ar III], [O IV] allows a detailed diagnostic of the ionized medium and the exciting continuum. We have used the photoionization code CLOUDY version 84.12 (Ferland 1993) updated with the [Ar II] collision strength of Pelan and Berrington (1995) to infer the average effective temperature of the ionizing stars from the observed ratios of lines from different ionization stages of the *same* element. We have adopted an ionization parameter $U \approx -1$ constrained by the density of $\approx$3000 cm^{-3} obtained from the [S III] and [Ne III] line ratios, the Galactic center ionizing flux of $\approx 3\times10^{50}$ s^{-1} (see e.g. Genzel and Townes 1987) and a typical distance of 0.5 pc to the ion-

Send offprint requests to: D. Lutz

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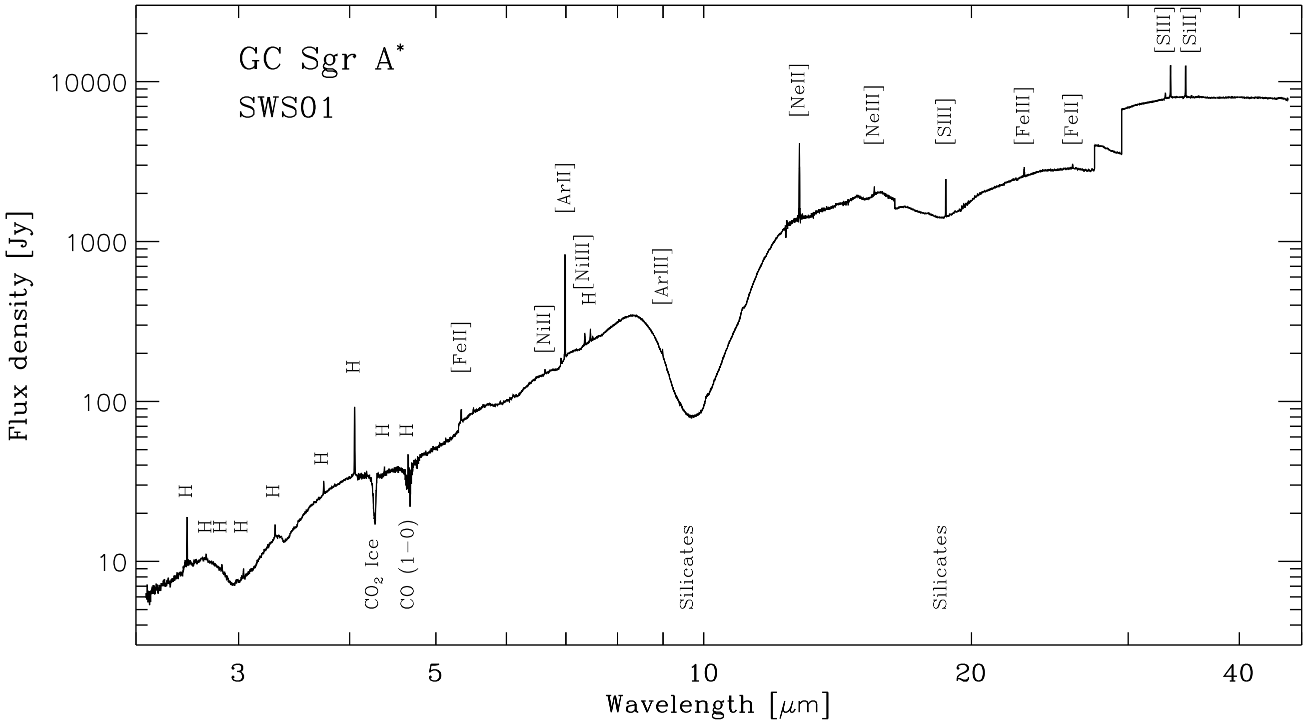

Fig. 1. SWS spectrum of the Galactic center. The aperture size used changes at 12.35, 27.5, and 29.5 μm

ized clouds. To estimate the impact of the adopted stellar spectra, we have used stellar atmosphere models of both Kurucz (1992) and Sellmaier et al. (1996). Using this and the three independent ratios [SIV]/[SIII], [ArIII]/[ArII], [NeIII]/[NeII] we infer that the average effective temperature is 35000±2000K, with the error estimate dominated by the effect of the adopted model atmospheres and the extinction correction within the silicate feature. Our observations improve the quantitative basis with respect to similar analyses based on a more restricted set of lines (e.g. Lacy 1980). A scenario with high densities and a harder stellar continuum (Shields and Ferland 1994) is difficult to reconcile with the measured line ratios.

The detection of weak [O IV] 26μm implies that the Galactic center must have an additional source of excitation, since nebulae illuminated by main sequence stars of the temperatures discussed above will not show sufficient [O IV]. While [O IV] emission can arise in a variety of sources - AGN, ionizing shocks or even planetary nebulae - the most conservative assumption in view of the direct near-infrared detection of Wolf-Rayet stars (Krabbe et al. 1995) is that locally there are regions centered on very hot stars in which the excitation is high enough to produce some [O IV]. The soft average radiation field, with a small harder component from evolved (WR) stars, indicates that the Galactic center has recently ($\approx$ 3 to 9×10^6 yrs ago) experienced a period of significant star formation, but is now forming stars at a lower rate.

Table 1. Absorption features

Wavelength [μm]	Identification
3.0	O-H stretch
3.4	Hydrocarbons
4.26	CO_2 ice
$\approx$4.66 (various)	^{12}CO fundamental
$\approx$4.77 (various)	^{13}CO fundamental
6.1	O-H stretch
6.8	Hydrocarbons/methanol
7.3	Hydrocarbons
7.7	Methane
9.7	Silicate
15.2	CO_2 ice
18	Silicate
34.6	OH

3. Absorption features

The SWS spectrum contains a number of new as well as known interstellar absorption features, which are listed in Table 1. We do not detect ‘PAH’ emission features, unlike spectra at positions on the circumnuclear ring. The carriers of the ‘PAH’ features are likely destroyed in the intense central radiation field ($\chi_{\rm FUV}$(GC) $\approx 10^{6.5}$ $\chi_{\rm FUV}$(ISRF)). The small number of transitions detected in the R and P branches of the CO fundamental is proof that this absorption originates in cold foreground gas. Similarly, the

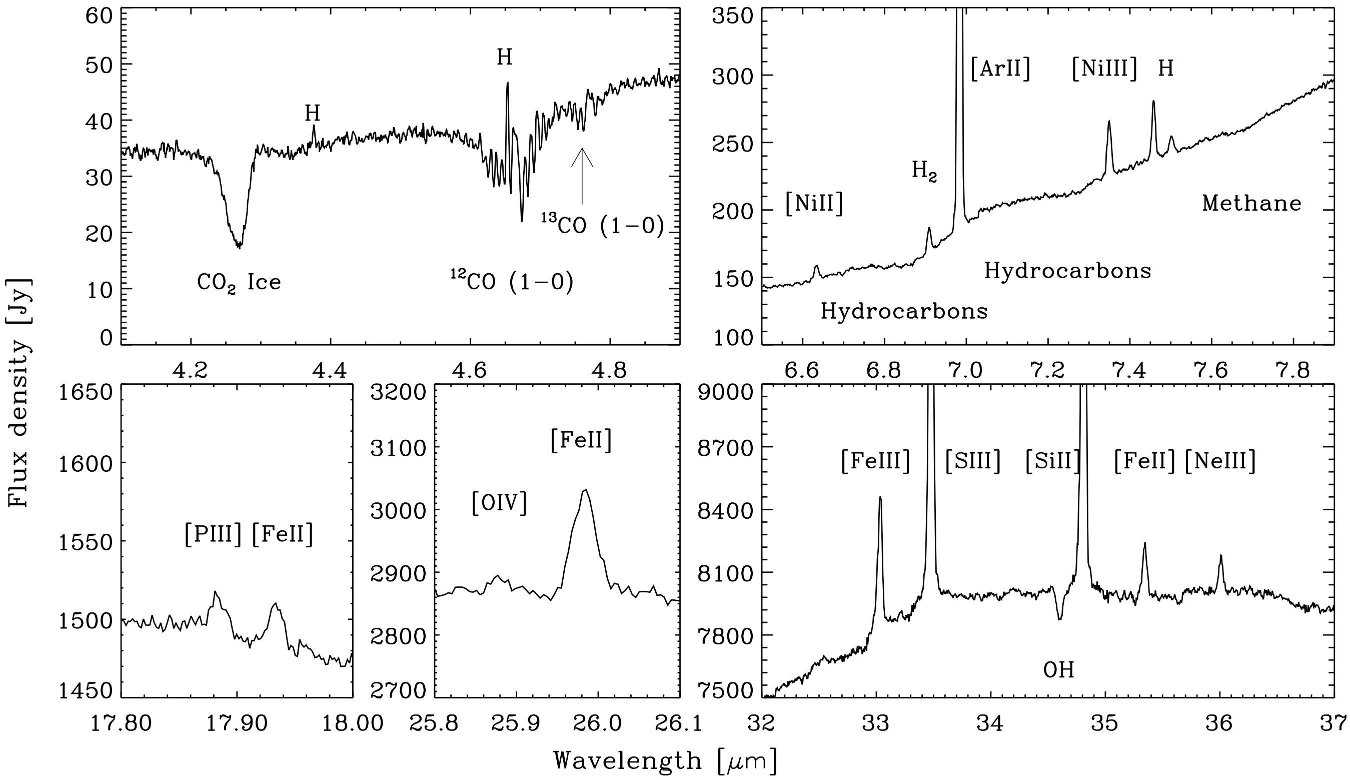

Fig. 2. Expanded display of selected regions from the Galactic center spectrum

presence of ices like CO_2 and methane indicates that part of the extinguishing column must be in a molecular cloud environment rather than in the diffuse ISM (see Whittet et al. (1996) for a discussion of the CO_2 ice features). Our spectrum does show a smooth broad 6.1μm feature, but not the substructures at 5.5 and 5.8μm ascribed to carbonyl groups by Tielens et al. (1996). Several of the features are ascribed to hydrocarbons, including the 7.3μm feature expected on the basis of the presence of the 6.8μm feature (Tielens et al. 1996).

4. Extinction law

We have used the hydrogen recombination lines detected between 2.5 and 9 μm to probe the extinction law in this wavelength range. For the Galactic center and the spatial scale of the ISO aperture, one can ignore problems that might arise in such an analysis in case of poorly known or inhomogeneous extinction. To determine an extinction law by comparison between observed fluxes and expected fluxes predicted from case B, it is necessary to know the extinction at one particular wavelength. We adopted the K band extinction of 3.47 mag inferred by Rieke, Rieke and Paul (1989) and extrapolated to the 'pivot' wavelength 2.625μm (Brackett β) assuming a $\lambda^{-1.75}$ extinction law. The resulting extinction curve is shown in Fig. 3. We confirmed our result against effects of calibration uncertainties by comparing the line fluxes to H line fluxes measured in NGC7027 with SWS and reduced in the same way. Our finding of high extinction is unaffected by a stellar wind contribution to the H lines since already Brackett γ is almost exclusively of nebular origin.

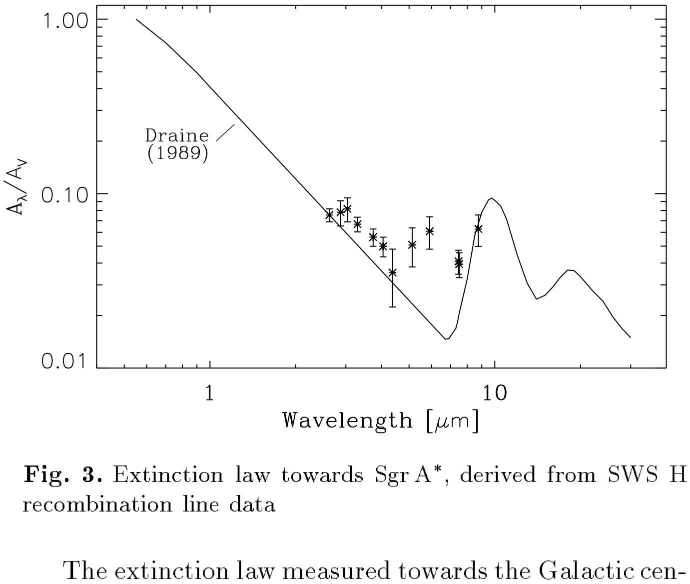

Fig. 3. Extinction law towards Sgr A*, derived from SWS H recombination line data

The extinction law measured towards the Galactic center clearly lacks the pronounced minimum in the 4–8μm region expected for standard graphite-silicate mixes (e.g. Draine, 1989). Additional contributors to the extinction must be present. Part of these may be the carriers of the absorption features like the 3μm 'ice' feature, which appears to imprint on the extinction curve, but a more continuous component due to e.g. iron/metal sulphides or metal oxides might also be involved. Since most of the extinction to the Galactic center arises in the foreground ISM rather than locally, it is likely that the new extinction curve is more widely applicable.

Table 2. Fluxes of selected emission lines

Identification	Lambda [μm]	Measured [W cm^{-2}]	Corrected[a] [W cm^{-2}]
[FeII]	1.533	DePoy '92	4.4e-18
[FeII]	1.644	DePoy '92	1.3e-17
[FeIII]	2.218	Lutz et al. '93	5.9e-19
[FeII]	5.340	1.6e-18	5.5e-18
[NiII]	6.636	8.9e-19	3.1e-18
[ArII]	6.985	4.4e-17	1.6e-16
[NiIII]	7.349	2.4e-18	9.6e-18
[ArIII]	8.991	8.1e-19	1.4e-17
[SIV]	10.51	(SWS02) 1.1e-19	1.9e-18
[NeII]	12.81	8.7e-17	2.5e-16
[NeIII]	15.55	5.7e-18	1.1e-17
[FeII]	17.93	3.4e-19	7.8e-19
[SIII]	18.71	1.6e-17	3.7e-17
[FeIII]	22.93	7.2e-18	1.3e-17
[OIV]	25.89	5.2e-19	8.3e-19
[FeII]	25.99	2.8e-18	3.5e-18
[FeIII]	33.03	9.5e-18	6.7e-18
[FeII]	35.34	2.0e-18	1.9e-18

[a] Corrected to a $14'' \times 20''$ aperture and for extinction.

5. OH absorption and pumping of OH emission

An unresolved absorption feature with an equivalent width of 0.0011μm (10 km/s) is detected at a wavelength of 34.6μm. The absorption is due to the blended $^2\Pi_{3/2}, J=3/2 \rightarrow ^2\Pi_{1/2}, J=5/2$ transitions of OH. Genzel et al. (1985) discussed the role of this transitions for the radiative pumping of longer wavelength OH emission from the Galactic center. The OH absorption we observe towards Sgr A* corresponds to $\gtrsim 10^{48}$ absorbed pumping photons per second, assuming a large covering factor for the OH absorber. Taking into account that the 54μm $^2\Pi_{3/2}, J=3/2 \rightarrow ^2\Pi_{1/2}, J=3/2$ transitions not covered by this spectrum also contribute to the pumping, and that strong 35μm absoption is also seen in other ISO pointings towards the circumnuclear ring, it is possible to pump OH 163μm line emission with a rate of $\approx 1.5 \times 10^{49}\,\mathrm{s}^{-1}$ as measured by Genzel et al. 1985 for a larger beam towards the circumnuclear ring. Radiative pumping hence appears to be the major source of excitation of OH emission from the Galactic center.

6. Iron and nickel emission

Table 2 lists the rich iron and nickel spectrum from our ISO observations and near-infrared observations taken from the literature. With a total of six lines observed, the excitation of [Fe II] can be well constrained. The disagreement between density $> 10^{4.5}\,\mathrm{cm}^{-3}$ derived from the ratio of the 1.533 and 1.644μm transitions and density $200\,\mathrm{cm}^{-3}$ inferred from the ratio of the 5.344 and 17.94μm lines triggered a detailed comparison with collisional excitation models. We conclude that *pure collisonal excitation cannot fit the observed line ratios, even if multiple temperature/density components are assumed*, and that other excitation mechanisms have to be taken into account. Because of the strong UV field in the Galactic center, fluorescent excitation of [Fe II] is an important possibility. Preliminary calculations (L. Lucy, priv. comm.) indicate a significant effect of fluorescence on the observed lines under Galactic center conditions. This calls for caution in the interpretation of [Fe II] emission of starburst galaxies, where similar radiation fields may be found.

The observed [Fe III] lines fit well the explanation of Lutz, Krabbe and Genzel (1993) for the bright near-infrared [Fe III] emission. [Fe III] is excited under H II region conditions with electron temperature below 10000 K in the 'mini-cavity' region which has an increased gas phase iron abundance due to grain destruction by a past shock. A higher electron temperature, as required for direct shock excitation, is ruled out by the ratio of ISO lines to near-infrared lines.

Ni^+ and Ni^{++} have very similar excitation and ionization energies to Fe^+ and Fe^{++} and will hence be found in closely similar regions. Under the assumption of collisional excitation, the ratios of Ni to Fe lines indicate an overabundance of Nickel for both ionization stages. This should however be viewed with caution since [Ni II] emission is affected by fluorescence too (Lucy, 1995), while the interpretation of [Ni III] is hampered by the lack of accurate atomic data.

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