

DUST EMISSION FEATURES IN NGC 7023 BETWEEN 0.35 AND 2.5 MICRONS: EXTENDED RED EMISSION (0.7 MICRONS) AND TWO NEW EMISSION FEATURES (1.15 AND 1.5 MICRONS)

KARL D. GORDON,¹ ADOLF N. WITT,² RICHARD J. RUDY,³ R. C. PUETTER,⁴ DAVID K. LYNCH,³ S. MAZUK,³
K. A. MISSELT,^{5,6} GEOFFREY C. CLAYTON,^{5,6} AND TRACY L. SMITH²

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ABSTRACT

We present 0.35–2.5 μm spectra of the south and northwest filaments in the reflection nebula NGC 7023. These spectra were used to test the theory of Seahra & Duley that carbon nanoparticles are responsible for extended red emission (ERE). Our spectra fail to show their predicted second emission band at 1.0 μm even though both filaments exhibit strong emission in the familiar 0.7 μm ERE band. The northwest filament spectrum does show one, and possibly two, new dust emission features in the near-infrared. We clearly detect a strong emission band at 1.5 μm which we tentatively attribute to $\beta\text{-FeSi}_2$ grains. We tentatively detect a weaker emission band at 1.15 μm which coincides with the location expected for transitions from the conduction band to midgap defect states of silicon nanoparticles. This is added evidence that silicon nanoparticles are responsible for ERE as they already can explain the observed behavior of the main visible ERE band.

Subject headings: dust, extinction — infrared: ISM: lines and bands — ISM: individual (NGC 7023) — ISM: lines and bands — reflection nebulae

On-line material: color figures

1. INTRODUCTION

Recently, Seahra & Duley (1999) proposed carbon nanoparticles as the material responsible for extended red emission (ERE). ERE is a broad ($\Delta\lambda \sim 0.1 \mu\text{m}$) emission band with a peak wavelength between 0.65 and 0.88 μm seen in many dusty astrophysical objects as well as the diffuse interstellar medium (ISM; Gordon, Witt, & Friedmann 1998 and references therein). A review of the observed characteristics of ERE can be found in Witt, Gordon, & Furton (1998). Among other proposed carriers for ERE are hydrogenated amorphous carbon (Duley 1985), coal (Papoular et al. 1996), quenched carbonaceous composite (Sakata et al. 1992), C_{60} (Webster 1993), and silicon nanoparticles (Ledoux et al. 1998; Witt et al. 1998; Ledoux et al. 2000). Identifying the material responsible for ERE is important as Gordon et al. (1998) have shown that this material must be a major component of dust grains. They found that the ERE in the diffuse interstellar medium on a galaxy-wide scale emits 4% of the energy absorbed by dust at wavelengths below 0.55 μm . If ERE could be convincingly identified with carbon nanoparticles, this could have implications

on the carriers of the 2175 \AA extinction bump and 3.4 μm CH_n absorption feature as both have also been attributed to carbon nanoparticles (Herlin et al. 1998; Schnaiter et al. 1998, 1999; Duley & Seahra 1999; Seahra & Duley 1999).

Seahra & Duley (1999) modeled the photoluminescence spectrum expected for different-sized carbon nanoparticles. The carbon nanoparticles in their model are composed exclusively of carbon and hydrogen atoms with sp^2 bonds (i.e., aromatic bonds). In general, the term carbon nanoparticles refers to materials with a mixture of sp^2 and sp^3 bonds (i.e., aromatic and aliphatic bonds). Seahra & Duley (1999) specifically chose to model only sp^2 carbon nanoparticles to match the observed high photoluminescence efficiency of ERE in the diffuse ISM (Gordon et al. 1998). The Seahra & Duley (1999) model predicts an ERE spectrum with three peaks at 0.5, 0.7, and 1.0 μm . The 0.7 μm peak is the peak usually identified with ERE. The 0.5 μm peak has never been seen, and this fact is accounted for by Seahra & Duley (1999). In their model, the 0.5 μm peak is produced by the smallest carbon particles. They point out that the environments where good ERE spectra exist are those with harsh UV radiation fields which will destroy all carbon nanoparticles with fewer than 50 carbon atoms. This effectively removes the 0.5 μm peak from the emission spectrum of ERE. There is an observed ERE spectrum of a high-latitude cirrus cloud where the 0.5 μm sideband might be expected, but it is not of sufficient signal-to-noise ratio to detect the 0.5 μm peak (Szomoru & Guhathakurta 1998). The search for the predicted 1.0 μm band was the motivation for this work. Previous to this paper, no published 1.0 μm spectra existed of a dusty object showing the familiar 0.7 μm ERE feature.

In order to test the prediction of a 1.0 μm feature associated with ERE-emitting dust, we have taken 0.35–2.5 μm spectra of two filaments in NGC 7023. NGC 7023 is the well-known reflection nebula illuminated by the Herbig Be star HD 200775 (Witt & Cottrell 1980; Witt et al. 1992; Sellgren, Werner, & Dinerstein 1992; Lemaire et al. 1996).

¹ Steward Observatory, University of Arizona, Tucson, AZ 85721; kgordon@as.arizona.edu.

² Ritter Astrophysical Research Center, University of Toledo, Toledo, OH 43606; awitt@dusty.astro.utoledo.edu; tsmith@astro1.astro.utoledo.edu.

³ Space Science Applications Laboratory, M2/266, The Aerospace Corporation, P.O. Box 92957, Los Angeles, CA 90009; richard.j.rudy@aero.org, david.k.lynych@aero.org, steve.mazuk@aero.org.

⁴ Center for Astrophysics and Space Sciences, C-0111, University of California, San Diego, La Jolla, CA 92093; rpuetter@ucsd.edu.

⁵ Department of Physics and Astronomy, Louisiana State University, Baton Rouge, LA 70803; gclayton@fenway.phys.lsu.edu, misselt@fenway.phys.lsu.edu.

⁶ Visiting Astronomer, Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under cooperative agreement with the National Science Foundation.

The two filaments we observed are well-known photo-dissociation regions which have been studied extensively at many wavelengths (Fuente et al. 2000 and references therein). These filaments are the tips of fingers of molecular material, as seen in CO, which point toward HD 200775 (Gerin et al. 1998). The filaments have been observed to emit ERE (Witt & Boroson 1990), many H₂ emission lines (Lemaire et al. 1996, 1999; Martini, Sellgren, & Hora 1997, hereafter M97; Martini, Sellgren, & DePoy 1999, hereafter M99), continuum emission from transitionally heated small dust particles (Sellgren 1983; Sellgren et al. 1992), and the aromatic infrared features (Sellgren et al. 1985; Cesarsky et al. 1996; Moutou et al. 1999; Uchida et al. 2000). The two filaments are composed of molecular cloud material that is being uncovered and modified by the UV-strong spectrum of HD 200775. This results in a rich spectrum of dust and gas emission features. In addition to the dust and molecular emission features listed above, the filaments are also known emitters of atomic hydrogen, carbon, and oxygen (Fuente et al. 2000). Interestingly, the emission from atomic silicon (Si II 34.8 μ m) appears strongly enhanced between the filaments and the illuminating star (Fuente et al. 2000). This implies that there is a transition from the solid to the gas phase of silicon at the filament edge.

2. OBSERVATIONS

Long-slit optical spectra of NGC 7023 were obtained at KPNO with the GoldCam spectrometer on the 2.1 m telescope on 1998 June 27 in photometric conditions. Observations were carried out using grating No. 201 with a slit width of 3", resulting in a spectral range of 0.35–1.0 μ m with a resolution of 18 Å (FWHM), as measured from night sky lines. Two 5 s exposures of HD 200775 were obtained along with three 900 s exposures of NGC 7023; both sets of observations were obtained at an air mass of 1.3. For the observations of NGC 7023, the 5' long slit was positioned 20" west of HD 200775 at a position angle of 5°. Standard reduction steps were performed using IRAF, and the details of the reduction are given in Misselt, Clayton, & Gordon (1999). The HD 200775 spectra were extracted from a 11"7

\times 3" wide region centered on the star. The sky emission was subtracted using sky spectra determined from positions above and below the star. Nebular spectra were extracted for the northwest and south filaments and their sky subtraction was done using sky spectra measured near the ends of the slit.

The positions, aperture sizes, and position angles of the northwest and south filament spectra used in this paper are given in Table 1. The optical spectra are designated NW-OPT and S-OPT for the northwest and south filaments, respectively. The other entries are for the new near-infrared spectra presented in this paper (NW-NIR and S-NIR) and previously published near-infrared spectra (Martini et al. 1997, 1999). Figure 1 shows the positions of all the filament spectra on a WFPC2/F606W image constructed from *HST* archival observations (Stapelfeldt et al. 1997).

Our near-infrared spectrophotometry of the NGC 7023 filaments and its illuminating star HD 200775 were acquired with the 3 m Shane reflector of Lick Observatory. The northwest and south filaments (NW-NIR and S-NIR in Table 1) were observed on 1999 August 30 (UT), and HD 200775 was observed on both 1999 August 28 and 30 (UT). The instrument used was the Near Infrared Imaging Spectrograph (NIRIS). A detailed description of the instrument, a two-channel, long-slit spectrograph operating from 0.8 to 2.5 μ m, is given by Rudy, Puetter, & Mazuk (1999). The spectrograph has a beam splitter at 1.4 μ m which feeds two arrays, allowing for simultaneous observations below and above 1.4 μ m. The arrays do not cover the entire spectral range in one setting, but each requires three settings to cover (with overlaps) the entire 0.8–2.5 μ m range. The resolution of the spectra is 18 and 36 Å for wavelengths shorter and longer than 1.4 μ m, respectively.

For the observations of the south filament, the brightest portion of the filament was centered visually in one-half of the east/west oriented slit. For the northwest filament, the brightest portion of the filament was centered visually in one-half of a northwest/southeast (position angle = 60°) oriented slit. To facilitate removal of the telluric background emission, spectra were acquired with the filament

TABLE 1
FILAMENT OBSERVATIONS

Name	Wavelength (μ m)	Position ^a (arcsec)	Aperture (arcsec)	Position Angle (deg)	Reference
Northwest Filament					
NW-OPT	0.35–0.9	14.5 W, 52 N	3 \times 21.1	5.7	1
NW-NIR	0.85–2.5	46 W, 26 N	3 \times 45	60	1
NW-NIR(M97)	1.5–2.5	40 W, 34 N	0.6 \times 5	0	2
NW-NIR(M99-N)	1.2–2.5	27 W, 48.5 N	4.5 \times 9	0	3
NW-NIR(M99-H2)	1.2–2.5	27 W, 36.5 N	4.5 \times 9	0	3
NW-NIR(M99-S)	1.2–2.5	27 W, 22 N	4.5 \times 9	0	3
South Filament					
S-OPT	0.35–0.9	27 W, 71 S	3 \times 13.3	5.7	1
S-NIR	0.85–2.5	11 W, 66 N	3 \times 45	90	1
S-NIR(M97)	1.5–2.5	22 W, 66 S	0.6 \times 5	0	2

^a Positions are referenced to HD 200775 (21^h01^m36^s.92, +68°09'47".763, 2000.0), the central star of NGC 7023.

REFERENCES.—(1) This work; (2) Martini, Sellgren, & Hora 1997; (3) Martini, Sellgren, & DePoy 1999.

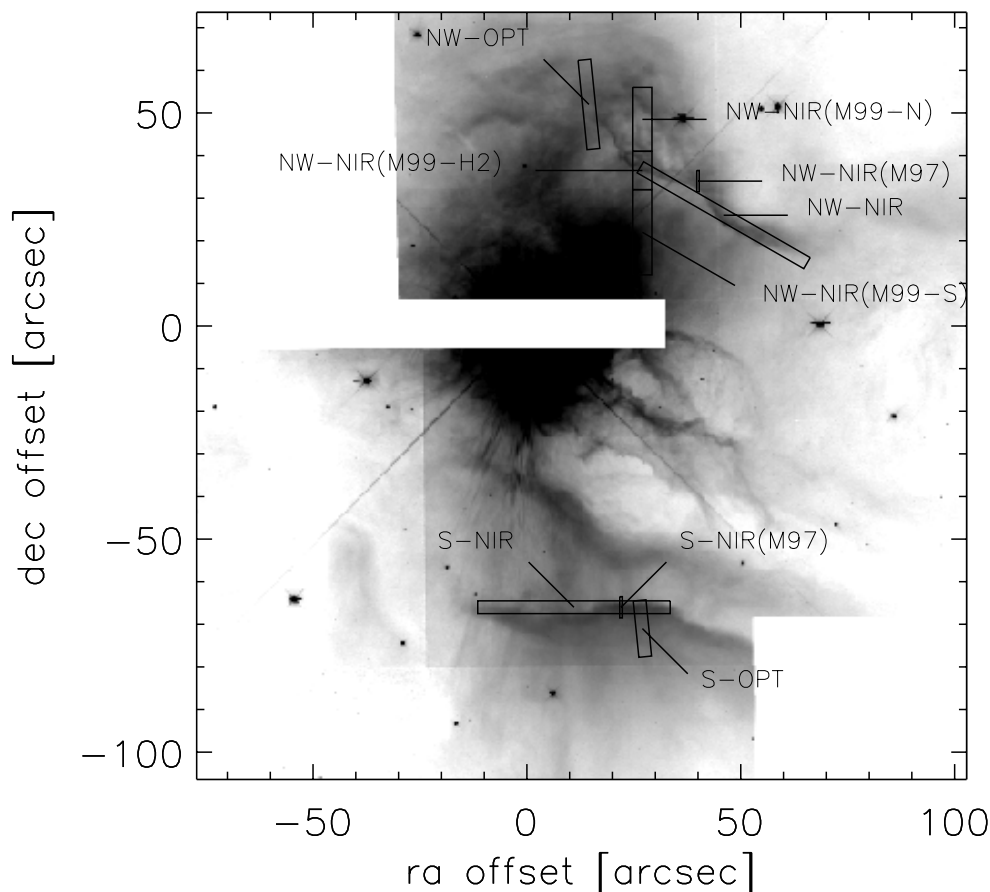


FIG. 1.—Positions of optical and near-IR spectra are shown on a WFPC2/F606W image of NGC 7023 constructed from *HST* archival observations (No. 5983, Stapelfeldt et al. 1997). Eight individual F606W images were used to construct the image, four at each of two positions, with a range of exposure times. The total exposure time for final image was 1905 s. The positions, sizes, and position angles for all the spectra are given in Table 1. [See the electronic edition of the Journal for a color version of this figure.]

positioned in one half (position 1) and then the other half (position 2) of the slit. At each spectral setting, four spectra, with exposure times of 25.5 s, were taken in the pattern of position 1, 2, 2, and 1. The total exposure time for the filament spectra were 102 s. The dimensions of the slit were $3'' \times 120''$. The data from a $45''$ swath along the slit at each of the two positions were combined to produce the filament spectrum. For the observations of HD 200775, a $20''$ telescope “nod” was used to separate the two observing positions. The individual exposure times for HD 200775 were 0.5 s, and 20 exposures were taken at each spectral setting. The final spectrum of HD 200775 is a combination of the data taken on 1999 August 28 and 30.

The comparison star used to remove the instrumental response and the effects of atmospheric absorption and to determine the absolute flux level for both the filaments and their illuminating star on 1999 August 30 was HR 7967, a G8 III star. The visual magnitude of $V = 6.41$ from the Bright Star Catalog (Hoffleit & Jaschek 1982) and the $V-K$ color for a G8 giant (Koornneef 1983) implies a K magnitude of 4.25. The intrinsic spectral shape of HR 7967 was removed from this ratio by using the model for this spectral type from Kurucz (1991). On 1999 August 28, the comparison star was 16 Cyg B (HR 7504), a G3 V star. The positions, aperture sizes, and position angles of these near-infrared filament spectra are given in Table 1 and plotted in Figure 1.

The combined $0.35\text{--}2.5\ \mu\text{m}$ spectrum of HD 200775, the illuminating star of NGC 7023, is plotted in Figure 2. In addition, optical and near-infrared photometry for HD 200775 are plotted (Allen 1973; Sellgren 1983; Witt & Schild 1988; Sellgren, Werner, & Allamondola 1996; Herbst & Shevchenko 1999). The optical spectrum was multiplied by 1.05 to make it match the optical photometry and the overlap region with the near-IR spectroscopy. This adjustment could be due to the uncertainties in the absolute calibration of the optical spectroscopy or the known variation in the flux levels for HD 200775 (Herbst & Shevchenko 1999), a Herbig Be star. The good agreement between the optical and near-IR spectra in the overlap region (Fig. 2, inset plot) in both continuum shape and line features increases our confidence in both observations.

Our new near-infrared spectra of the south and northwest filaments are plotted along with those from the literature (Martini et al. 1997, 1999) in Figure 3. As the literature observations were taken with different apertures and on similar, but different, locations in each filament (see Table 1 and Fig. 1), we have scaled their observations to match the overall level of our new H -band observations. For the south filament (Fig. 3a), both spectra [S-NIR and S-NIR(M97)] are very similar in the H band but show different K -band continuum levels. For the northwest filament (Fig. 3b), the H -band continuum is very similar between NW-NIR and NW-NIR(M97), but both spectra have a much different

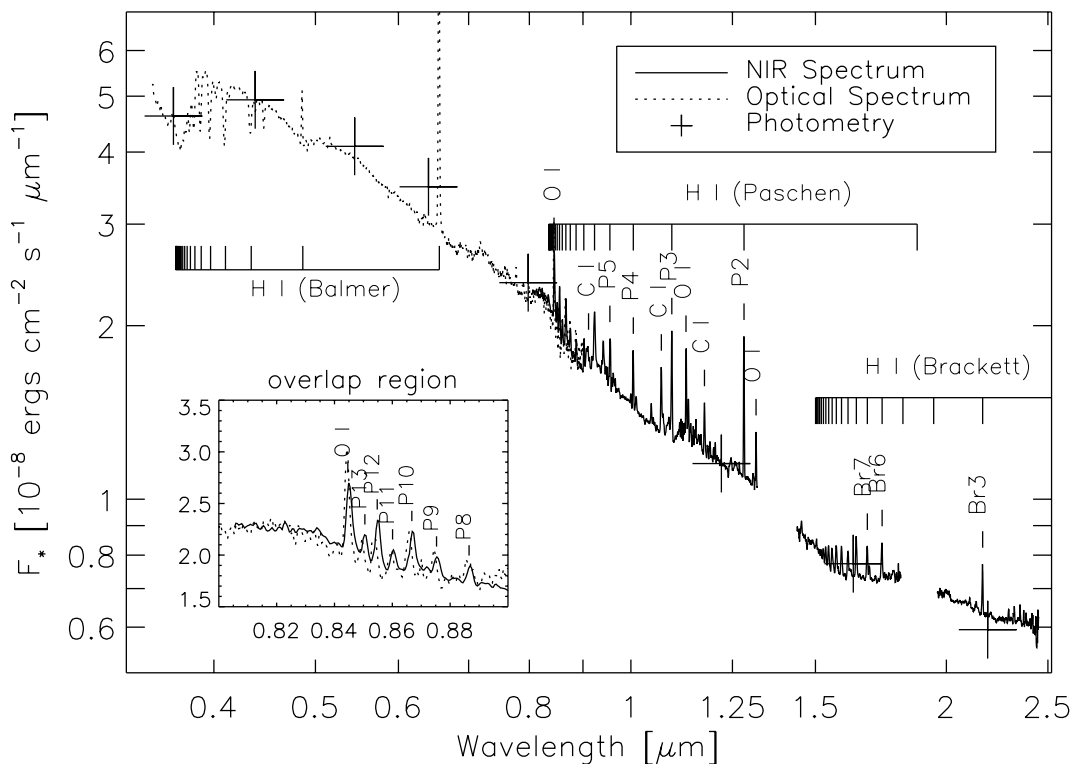


FIG. 2.—Full optical and near-infrared spectrum of HD 200775 is plotted. Photometry from various sources is plotted as crosses. The Balmer, Paschen, and Brackett H I lines are labeled as well as the major O I and C I lines. The inset plot gives a closeup of the overlap region, illustrating the quality of the relative calibration of the optical and near-infrared observations. [See the electronic edition of the *Journal* for a color version of this figure.]

continuum shape than that of NW-NIR(M99-H2). The *K*-band spectra for all three northwest filament spectra are similar in continuum shape, with NW-NIR(M97) having a slightly higher overall level. The differences between spectra are not surprising as the spectra from different sources were taken with different apertures on different positions in each filament.

As we have identified the origin of the northwest filament *H*-band continuum shape with a new dust emission feature (see § 3.3), it is important to point out that the *H*-band continuum shape is very unlikely to be the result of an error in the way the data were taken or reduced. If there was such an error, it would be very unlikely that the *H*-band spectral shapes of both the south and northwest filaments would

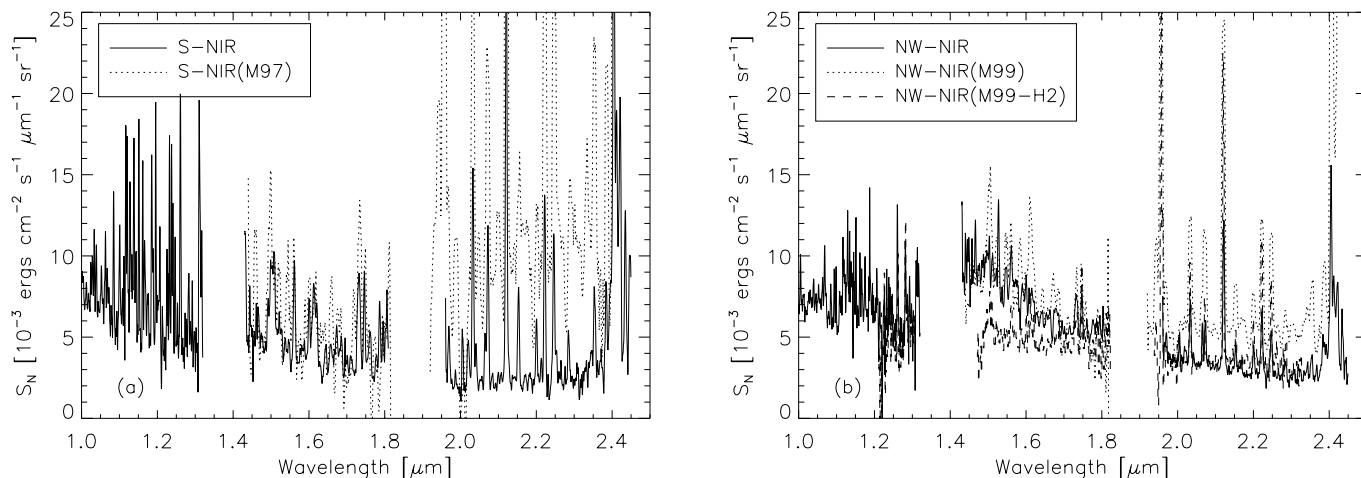


FIG. 3.—Near-infrared spectra for the (a) south and (b) northwest filaments are shown for the Martini et al. (1997) [S-NIR(M97) and NW-NIR(M97)], *H* and *K* bands only], the Martini et al. (1999) NW-NIR(M99-H2), *J*, *H*, and *K* bands, and our new observations (S-NIR and NW-NIR). The Martini et al. (1997) spectra have been smoothed with a 5 pixel wide boxcar and have been multiplied by factors of 10 and 2.5 for (a) and (b), respectively, to ease the spectral shape comparisons. The Martini et al. (1999) spectrum (b only) has been multiplied by 0.5 for the same reason. The noiselike appearance of the near-infrared spectra is due to a virtual forest of H₂ emission lines. [See the electronic edition of the *Journal* for a color version of this figure.]

agree between our spectra (S-NIR and NW-NIR) and those of Martini et al. (1997) [S-NIR(M97) and NW-NIR(M97)] as each was taken by a different instrument on a different telescope by different observers and reduced by different people. Therefore, we conclude that the spectral shape of the northwest *H*-band spectra is real.

3. DISCUSSION

With the new spectra presented in this paper, we can study the dust scattering and emission in NGC 7023 between 0.35 and 2.5 μm . This allows us to characterize the dust scattering and emission in the optical and near-infrared and test the prediction of Seahra & Duley (1999). The 0.35–2.5 μm spectra of both filaments are plotted in Figure 4. Both filament spectra have been divided by the spectrum of HD 200775, leaving ratio spectra whose shape is only dependent on the dust scattering, dust emission, and gas emission. The gas emission gives rise to the [C I] and H_2 emission lines, the analysis of which is beyond the scope of this paper. The dust scattering and emission mainly affects the continuum shape of these ratio spectra while the gas emission is responsible for most of the emission lines.

3.1. Scattered Light

In Figure 4, the theoretical ratio spectra for different dust scattering situations have been plotted in addition to the filament ratio spectra. The theoretical spectra have been computed using a model presented in Witt (1985). The model equations can be used to compute the ratio spectra for single-angle dust scattering. This is the situation for the two filaments of NGC 7023 which are discrete density enhancements in the reflection nebula (Gerin et al. 1998). The theoretical ratio spectra were computed using average Milky Way dust grain properties (albedo, scattering phase function asymmetry, and extinction curve) (Wolff, Clayton, & Gordon 2000). The cases plotted in Figure 4 are for infinite optical depth ($\tau_V = \infty$), very optically thin ($\tau_V =$

0.01), and a best estimate case ($\tau_V = 1$ for panel *a* and $\tau_V = 5$ for panel *b*). We assumed the optical depths from the star and the filament to the observer were equal. All the theoretical curves were normalized to the observed value at 0.45 μm . The scattering angles which gave reasonable fits to the data were 90° and 60° for the south (Fig. 4*a*) and northwest (Fig. 4*b*) filaments, respectively. It was only possible to get reasonable fits to the data as the continuum in the near-infrared is due to both dust scattered stellar light and emission from transitionally heated small dust particles (Sellgren et al. 1992). As a result, the fraction of the ratio spectrum due to dust scattering in the near-infrared is decreasing as the wavelength increases. The emission from transitionally heated small dust particles starts in the *J* band and increases rapidly to the *K* band.

3.2. Absence of 1 μm Carbon Nanoparticles Feature

Seahra & Duley (1999) predicted that ERE is due to photoluminescence from sp^2 coordinated carbon nanoparticles. For the conditions present in NGC 7023, they predicted that ERE produces 0.7 and 1.0 μm emission bands (see their Fig. 4). Both the observed filaments exhibit strong ERE bands near 0.7 μm as seen in Figure 4 and previous work (Witt & Schild 1988; Witt & Boroson 1990). Neither filament shows a 1.0 μm feature as predicted by Seahra & Duley (1999) for carbon nanoparticles. The northwest filament does show tentative evidence for a feature peaking at 1.15 μm (see Fig. 5 and § 3.3), but this feature peaks at a significantly longer wavelength than predicted by Seahra & Duley (1999) and so is unlikely to be due to carbon nanoparticles. The central wavelength of the 1.0 μm peak predicted by Seahra & Duley (1999) varies very little ($<0.02 \mu\text{m}$) for a large range of carbon particle sizes ($\langle N_C \rangle = 125\text{--}500$) and dispersions around each size ($\sigma = 125\text{--}500$). The lack of any feature at 1.0 μm in both filaments calls into question the identification of carbon nanoparticles as modeled by Seahra & Duley (1999) as the carrier of ERE. We do note that Seahra & Duley (1999) do

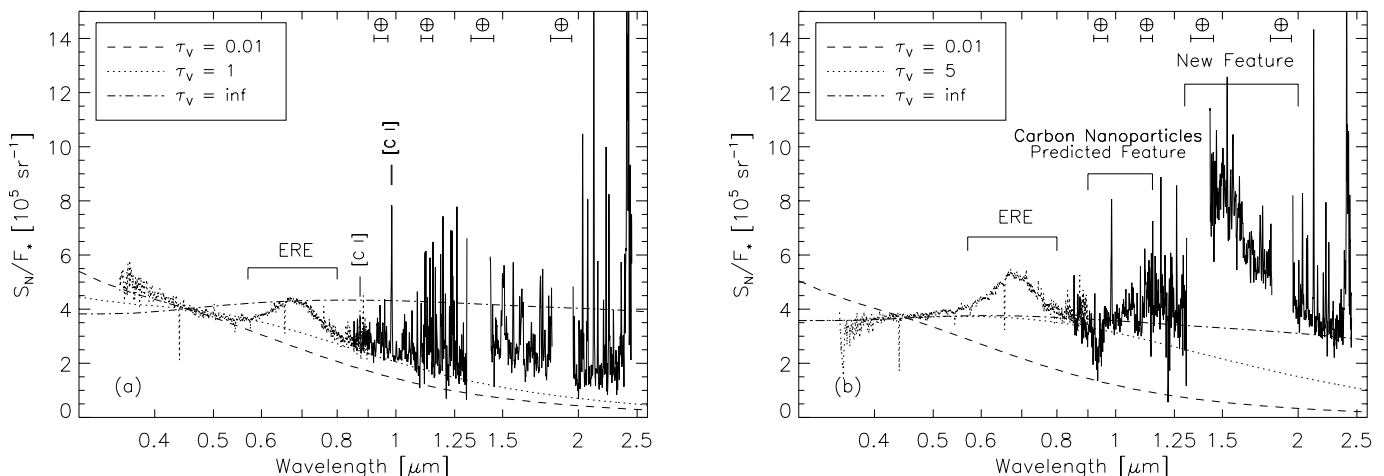


FIG. 4.—Combined optical and near-infrared spectra for the (a) south and (b) northwest filaments are shown. The spectra are displayed as the nebular surface brightness to stellar flux (S_N/F_*) ratio. To compensate for offsets caused by the different optical and near-infrared apertures used, the near-infrared spectra in (a) were multiplied by 0.6 to match the optical data. The noiselike appearance of the near-infrared spectra is due to a virtual forest of H_2 emission lines. Almost all of the lines in the near-infrared are due to H_2 , with the notable exception of the two C I lines identified in (a). The locations of the major atmospheric absorptions in the near-infrared are shown at the top of both plots. The smooth lines are theoretical ratio spectra computed as discussed in § 3.1. [See the electronic edition of the *Journal* for a color version of this figure.]

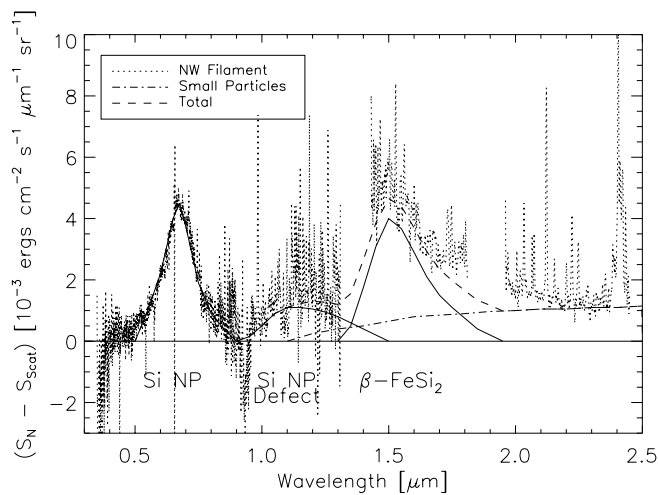


FIG. 5.—Northwest filament emission spectrum (observed minus scattered light model) is plotted (dotted line). In addition, profiles of the proposed carriers (solid lines), emission from transitionally heated small particles (dash-dotted line), and the total (dashed line) are plotted. The $0.7 \mu\text{m}$ silicon nanoparticle photoluminescence band is from Guha (1997) and Ehbrecht et al. (1997). The $1.1 \mu\text{m}$ silicon nanoparticles defect band is from Fujii, Hayashi, & Yamamoto (1998); Fujii et al. (1999). The $1.5 \mu\text{m}$ $\beta\text{-FeSi}_2$ band is from Leong et al. (1996) and Suemasu et al. (1999). [See the electronic edition of the Journal for a color version of this figure.]

predict a weak $1.0 \mu\text{m}$ peak for a small subset ($\langle N_C \rangle \sim 125\text{--}200$ and $\sigma \sim 125\text{--}150$) of the size distributions of carbon nanoparticles they modeled (see Figs. 2 and 4) and state in their conclusions that there are mixtures with larger carbon nanoparticles which exhibit the main ERE peak around $0.8 \mu\text{m}$ and no $1.0 \mu\text{m}$ peak. But this does not correspond to the conditions in the NGC 7023 filaments which have their main ERE peaks near $0.7 \mu\text{m}$.

While the lack of the $1.0 \mu\text{m}$ peak in our observations does not rule out carbon nanoparticles as the source of ERE, it does diminish the probability that they are the source of ERE. This is especially true when the minimum 10% photoluminescence efficiency of ERE in the diffuse ISM (Gordon et al. 1998) is considered. Seahra & Duley (1999) chose to model only carbon nanoparticles with sp^2 bonds specifically so that the particles would have a high photoluminescence efficiency. Carbon nanoparticles with sp^2 and sp^3 bonds of different sizes have been produced in the lab (Herlin et al. 1998) and have a negligible photoluminescence efficiency (N. Herlin 2000, private communication). Thus, the main problem with carbon nanoparticles being responsible for ERE is their low efficiency as measured in the laboratory. The Seahra & Duley (1999) carbon nanoparticles model can account for this, but the lack of a $1.0 \mu\text{m}$ peak in NGC 7023 does not confirm their model. It is likely the Seahra & Duley (1999) model can be modified to account for our new observations (W. Duley 2000, private communication), but their model needs to make predictions which are confirmed by observations or be directly supported by laboratory work before carbon nanoparticles can be convincingly identified with ERE. As such, it is worth noting that silicon nanoparticles do a better job of reproducing the observed characteristics of ERE and their characteristics are supported by laboratory measurements (Ledoux et al. 1998; Witt et al. 1998; Credo, Mason, & Buratto 1999; Ledoux et al. 2000). We have

found tentative additional evidence for silicon nanoparticles in our observations which is discussed below.

3.3. Two New Dust Emission Features

The unexpected result of this study is the evidence for at least one, and possibly two, previously unobserved, broad emission features which peak in the near-infrared. Examining our spectra of NGC 7023 and those in the literature (Martini et al. 1997, 1999), the new features are seen in only part of the northwest filament (see Figs. 1 and 3). In order to show the profiles and relative strengths of the new features as well as the ERE band, we display the spectrum of the intensity of the northwest filament, with the scattering spectrum for $\tau_v = 5$ (Fig. 4b) subtracted in Figure 5. This spectrum is due to excess emission arising from the dust and gas in the northwest filament. Here we will focus solely on the dust emission components.

We identify three discrete emission features, in addition to a broad continuum which increases in intensity toward longer wavelengths. This broad continuum has been previously identified as nonequilibrium thermal emission from stochastically heated tiny particles in the subnanometer size range (Sellgren et al. 1992). The discrete features in the northwest filament have peaks at 0.68 , 1.15 , and $1.50 \mu\text{m}$, and widths characteristic of solid-state photoluminescence bands. The $0.68 \mu\text{m}$ band is the well-known ERE band.

The strongest of the two new bands is at $1.50 \mu\text{m}$ and is similar in strength and width to the visible ERE band at $0.68 \mu\text{m}$. No interstellar band with these characteristics has ever been reported before in this wavelength region. Given the strength of this band, an origin in a photoluminescence process involving solids made from heavily depleted abundant refractory elements is strongly suggested. The only band we found, after an extensive search of the astronomy and physics literature, fitting this description is the photoluminescence band in the low-temperature, amorphous phase of iron disilicide ($\beta\text{-FeSi}_2$) (Leong et al. 1996; Suemasu et al. 1998, 1999; Filonov et al. 1999). Iron disilicide is a direct-bandgap semiconductor with a bandgap near 0.8 eV , in which cross-bandgap recombination of free electrons and holes produces photoluminescence similar to that observed in silicon nanoparticles. However, in contrast to the case in silicon, an indirect bandgap semiconductor FeSi_2 does not need to be in the form of nanoparticles in order to exhibit efficient photoluminescence. In fact, low-temperature FeSi_2 particles of about 100 nm diameter appear to be luminescing most efficiently, with the width of the band dependent upon the state of annealing, with relatively narrow bands seen only with annealing temperatures in excess of 900°C . These temperatures are not likely to occur in large dust grains located in the NGC 7023 filaments, as the radiation field density is unlikely to heat the dust grains to such high temperatures. Thus, both the width and relative strength of the band at $1.5 \mu\text{m}$ are consistent with photoluminescence by low-temperature iron disilicide grains. In Figure 5, we have plotted the laboratory FeSi_2 band profile that most closely fits the observed $1.5 \mu\text{m}$ feature. The observed profile does deviate from the laboratory profile on the long-wavelength side. This deviation may be due to the fact that the laboratory profile is for a single particle size and the observed profile is likely the result of a population of different-sized particles. We have no explanation at present why such grains are observable in the northwest filament and not in the south filament. More observations

of this interesting new band in other reflection nebulae and under a wider range of physical conditions are clearly needed.

Our tentative identification of the new 1.5 μm feature with FeSi₂ dust grains is supported by two recent papers (Ferrarotti et al. 2000; Henning 2000). Ferrarotti et al. (2000) performed chemical equilibrium calculations for a particular gas-phase mixture deficient in carbon and oxygen and found that solid FeSi is the first condensate of abundant refractory elements. They identify the previously unidentified, strong 47.5 μm feature in the spectrum of the evolved stars AFGL 4106 (Molster et al. 1999) as arising from FeSi grains. It is possible that FeSi₂ could also form in similar mixtures of refractory elements (H.-P. Gail 2000, private communication). Henning (2000) presents a laboratory spectrum of FeSi₂ grains from 10 to 70 μm . The main features of this spectrum are bands at 21, 27, and 30 μm , and similar bands have been seen in *IRAS* and *Infrared Space Observatory* data (Henning 2000). Combining these two papers and our work implies that FeSi₂ dust grains could very well be present in the interstellar medium. Additional observations are obviously needed, especially aperture matched observations from 1 to 35 μm .

The weaker of the two new bands peaks around 1.15 μm and its presence in the northwest filament spectrum is tentative at best. Additional observations are definitely required to confirm the presence of this feature. It is intriguing to note the wavelength location of the new 1.15 μm feature in light of recent laboratory work on silicon nanoparticles. Laboratory studies of photoluminescence of silicon nanoparticles in the form of porous silicon or matrix-embedded nanocrystallites (Meyer et al. 1993; Gardelis & Hamilton 1994; Petrova-Koch & Muschik 1995; Hill & Whaley 1996a, 1996b; Fujii, Hayashi, & Yamamoto 1998; Fujii et al. 1999) have produced evidence for the existence of a second, near-IR, photoluminescence band, in addition to the main optical band matching the ERE. The peak wavelengths of these two bands, both subject to quantum confinement, vary with the size of the emitting particles and are closely correlated by the relation

$$E_p(\text{IR}) = 0.43E_p(\text{ERE}) + 0.34, \quad (1)$$

where $E_p(\text{IR})$ and $E_p(\text{ERE})$ are the peak energies of the near-IR band and the visible band in eV, respectively (Hill & Whaley 1996b). With the ERE observed to peak at 0.68 μm in the northwest filament, equation (1) predicts a peak wavelength for the near-IR band of 1.1 μm . We have indicated the silicon nanoparticle bands in accordance with laboratory results in Figure 5. They provide very satisfactory fits to the observational data.

The principal ERE band in the visible is attributed to recombination of free electron-hole pairs in silicon nanoparticles (Si NP in Fig. 5) (Witt et al. 1998), while the near-IR band from the same type of particle is attributed to recombination of photoexcited electrons from the conduction band to in-bandgap defect sites associated with Si dangling bonds at the surfaces of silicon nanocrystallites (Fujii, Hayashi, & Yamamoto 1998). The near-IR band is observed in the laboratory only at temperatures of $T < 150$ K, while the visible band remains strong at higher temperatures. The relative strength of the two bands also depends on the degree of passivation of surface dangling bonds. With increasing passivation (e.g., with oxygen atoms) the near-IR band decreases in strength while the

visible band gains in strength. The fact that only the northwest filament shows the near-IR band near 1.15 μm but both the south and the northwest filaments display the visible ERE band is thus easily explained. Either the maximum temperature reached by individual nanoparticles in the south filament upon absorption of individual photons is higher than the corresponding temperature of nanoparticles in the northwest filament or the degree of passivation is higher in the south filament. The first explanation seems more likely in view of the higher optical depth of the northwest filament ($\tau_V \sim 5$) compared to the more optically thin south filament ($\tau_V \sim 1$). Energetic photons are thus less likely to reach nanoparticles in the northwest filament. Witt et al. (1998) estimated that a 1.7 nm diameter Si nanoparticle experiences a temperature increase of ~ 170 K upon absorbing a 10 eV photon. We conclude that the average maximum temperature of the Si nanoparticles in the northwest filament must be lower than those in the south filament, low enough to allow the near-IR band to be observable.

Given that the visible ERE band has been observed with peak wavelengths ranging from 0.65 to 0.88 μm in different environments, equation (1) predicts the possible existence of corresponding near-IR bands with peak wavelengths spanning the range from 1.07 to 1.31 μm . Detection of such bands with wavelengths fitting the correlation in equation (1) would be a powerful confirmation of the silicon nanoparticle model for the ERE. Additional observations in the near-IR region such as reported here are clearly needed.

4. CONCLUSIONS

From new 0.35–2.5 μm spectra of the south and northwest filaments in the reflection nebula NGC 7023, we conclude the following:

1. The 1.0 μm feature predicted by Seahra & Duley (1999) is not seen. This result when combined with the negligible measured photoluminescence efficiency of carbon nanoparticles calls into question the identification of carbon nanoparticles as the source for ERE.
2. We have discovered a new strong and broad dust emission feature which peaks at 1.5 μm , and we tentatively identify it with photoluminescence from β -FeSi₂ grains.
3. We have also found tentative evidence for another new broad, dust emission feature at 1.15 μm . We identify this feature with photoluminescence from transitions from the conduction band to defect states in silicon nanoparticles. If this is correct, it lends support to the identification of silicon nanoparticles as the carrier of ERE.

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