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Loop Modeling of Coronal X-ray Spectra

I. General Properties

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Abstract. This work is motivated by the widely accepted paradigm that the structure and features of stellar coronae are determined by plasma magnetically confined in coronal loops. In particular we address the question whether it is possible to devise diagnostics amenable to reveal some physical and geometric characteristics of static coronal loops from X-ray observations. We show that single-loop coronal models may give spectra differing in several respects from one- and two-temperature models, the differences being probably observable already with ASCA/SIS. We find that the spectra of our loop models are essentially determined by the plasma below one pressure scale height; therefore we do not need to consider deviations from Spitzer's conductivity which occur in the very diluted upper atmosphere.

We also find that widening of cross section of the loops may give observable effects depending on loop parameters and that even a small fraction of the star's surface covered by compact coronal loops with dense plasma can easily dominate the emission from a corona and mask the emission from long and tenuous loops.

Finally we present an example of fitting a real ROSAT/PSPC observation with loop-emitted spectra.

Key words: Stars: coronae; Stars: late-type; Plasmas; Ultraviolet: stars; X-rays: stars

1. Introduction

The paradigm that the whole X-ray emitting corona is made of magnetic loops confining plasma has been derived from solar observations and has been extrapolated to stellar coronae, on the basis of considerable evidence, in work pioneered by G.S. Vaiana (cf. Linsky & Serio 1993, for a recent overview of such research). However, the detailed replication and interpretation of observed stellar features, e. g. luminosity, spectra and variability, has been based only very limitedly on loop modeling, for many reasons, including low photon statistics and moderate spectral resolution of the observations. Traditionally, instead, the oversimplified isothermal plasma model has been used for virtually all quantitative descriptions of stellar X-ray spectra: for early coronal observations as an immediate way to prove the thermal origin of the X-ray stellar emission, and thereafter as a straightforward and standard model for the fitting of many observations, most typically those made with instruments of low X-ray spectral resolution, such as the Channel Multiplier Array on board EXOSAT, the Imaging Proportional Counter on board the *Einstein* satellite and the Position Sensitive Proportional Counter (PSPC) on board ROSAT. The observations poorly fitted by a single isothermal model, instead, have been better fitted with the slightly more complex model having two isothermal components (Schmitt et al. 1990, Wood et al. 1994).

In spite of the significant improvement of instrumental capabilities, for instance with the Solid-state Imaging Spectrometer (SIS) on board ASCA, characterized by spectral resolution higher than the ROSAT/PSPC's one and by a significant photon collecting power, the observations are still interpreted and fitted in terms of contributions from

Send offprint requests to: A. Ciaravella one or two isothermal plasma components (cf. for instance White et al. 1994, Drake et al. 1994) with only limited attention to loop models (see, however, Ottmann 1993). It is our contention that data from the newest instruments, if not already some of those obtained from previous instruments, very likely require an interpretative model more refined than the isothermal model. Furthermore instruments with similar, or even better, capabilities will be available in the future, the most notable ones being those on board XMM and AXAF.

For these reasons we consider now very important to set up a project aimed at reconciling our picture of coronae dominated by loops with the tools for analyzing the experimental data. Our project will include, among other tasks, an exploration of the physical and geometrical effects most relevant for the X-ray spectrum emitted by a loop, the effects of loop multiplicity on the star's surface, the devising and testing of fitting procedures based on loop-emitted spectra.

This is the first paper of such a project. Here we revisit the models of static coronal loops in order to clarify the role of some important physical and geometrical loop parameters in determining the characteristics of the loop model spectra, and show some features potentially important in fitting the observational data. An accompanying paper (Maggio and Peres 1994; hereafter Paper II) is dedicated to extensive simulations of spectral fitting based on loop models. These two papers are intended to provide a first conceptual framework for forthcoming extensive applications to ROSAT/PSPC and ASCA/SIS observations. Future work will be dedicated to studies of spectra observable with planned instruments on board XMM and AXAF.

In this work, we first synthesize spectra from loop models over a wide range of loops characteristic parameters and compare them with those of isothermal models of equal effective temperature, emphasizing the spectral differences. We then study potential effects of departures from Spitzer's conductivity using the formulation of the coronal loop model, developed in Ciaravella, Peres and Serio (1991, 1993; henceforth CPS I and CPS II).

We extend these models to consider the effects of non-uniform cross section of the loop. Indeed, the hypothesis of constant loop cross section, although appropriate for small loops might not be so for long loops, as shown by observations with Yohkoh and the Normal Incidence X-ray Telescope (cf., for instance, Tsuneta & Lemen 1993; Uchida 1993; Golub 1993). In this respect, the widening of the loop cross section could, in principle, contribute significantly to the emission measure of high temperature plasma and affect the emitted spectrum.

Finally, we briefly consider model coronae made of two different loop structures with rather different physical conditions, dimensions and relative contributions to the emitted radiation mimicking, say, active regions and large scale structures. We postpone to future work an extensive study of this problem as well as further aspects such as a detailed comparison of loop spectra with a two temperature thermal model of coronae, the effects of changing elemental abundance and the implication on the analysis of specific observations.

The paper is so organized: in Sect. 2 we summarize the main characteristics of the static loop model and define the parameter space explored with our calculations; in Sect. 3 we describe our method to synthesize the spectrum emitted by a loop; in Sect. 4 we compare spectra of isothermal plasma with those emitted from coronal loops, analyze the influence of different physical effects on loop spectra and briefly discuss models of coronae with two kinds of loops; we draw our conclusions in Sect. 5.

2. Models of static coronal loops

In CPS I and CPS II we have revisited and extended the hydrostatic model of Serio et al. (1981), paying attention to the role of thermal transport even in the case of long electron mean free paths, and then studied some physical features of steady loops. Our model assumes that coronal plasma is confined inside a semicircular loop of semi-length L, mirror symmetric with respect to its apex and with constant cross section (see however also Sect. 4.3). The plasma is described as a fluid, in hydrostatic equilibrium under the effect of gravity, and with steady energy balance among a uniform heating input, optically thin radiative losses (Raymond et al. 1976) and thermal transport.

For thermal transport we have used three alternative formulations, namely Spitzer-Harm's (1953), non-local (Luciani et al. 1983) and limited free- streaming (Mannheimer 1977).

Table 1 reports the parameters characterizing all models studied in CPS I and II, and also used here: for each gravity value we have modeled the loop structures corresponding to all the combinations of base pressures and semi-lengths shown in Table 1.

The spectrum emitted by the optically thin plasma in the loop, in the range of temperature which we consider, i.e. from 2×10^4 K (the base of the transition region) to the temperature maximum in corona, can be computed taking into account the symmetry of the loop, as:

$$F(E) = 2 \int_0^L n_e(s) n_p(s) P(T(s), E)\ S(s)\ ds \tag{1}$$

Table 1. Parameters of coronal loop models

$g/g_\odot$	0.3	1.	3.	10.			
L (10^9 cm)	2.	6.	10	20.	50.		
p_0 (dyn cm^{-2})	0.03	0.1	0.3	1.	3.	10.	30.

(erg s^{-1} keV^{-1})

where E is the photon energy, L the loop semi-length, n_e and n_p are the electron and proton number densities respectively, T the temperature, S the loop cross sectional area and s the coordinate along the loop.

The emissivity function $P(T,E)$ (erg cm^3 s^{-1} keV^{-1}), in the band (or line) of interest, is a function of the plasma temperature, of photons energy and of the elemental abundances, and can account for contributions from free-bound, free-free, bound-free and two-photon processes; it is calculated with the Raymond's code (1989), and we always assume to deal with plasma with cosmic abundances and in ionization equilibrium.

In the case of coronae composed of many kinds of loops, one could model the coronal spectrum as the sum of several loop spectra, each weighted by a contributing fraction, that is:

$$F_{tot}(E) = 2\pi {R_\star}^2 \sum_i f_i \left(\int_0^{L_i} n_e(s) n_p(s) P(T,E)\ S(s)\ ds \right)_i \tag{2}$$

(erg s^{-1} keV^{-1})

where $R_\star$ is the stellar radius and f_i the fraction of stellar surface covered by the base of the loop, the index i running over the different kinds of loop structures. As a matter of fact in this paper we assume that the corona is made of one or, at most, two kinds of identical loop.

If we observed a source at a distance D with an instrument of effective area $A(E)$, the measurable quantity in the focal plane, namely the photon count rate, would be:

$$I(E) = \frac{1}{4\pi D^2} \frac{F_{tot}(E)}{E} A(E) \tag{3}$$

(photons s^{-1} keV^{-1})

for an instrument with infinite spectral resolution. Since, however, any instrument resolves the spectrum in a series of detector energy channels, and since an incident photon with a given energy has a finite probability to be detected in any of the nearby detectors energy channels, the observed spectrum is:

$$I(j) = \frac{2\pi {R_\star}^2}{4\pi D^2} \sum_i f_i \left(\int_0^{L_i} n_p(s) n_e(s) G(T(s),j)\ S(s)\ ds \right)_i \tag{4}$$

(photons s^{-1})

where j runs over the detector channels and $G(T(s),j)$ is the plasma emissivity convolved with the instrument response and energy response matrix $M(j,E)$:

$$G(T(s),j) \;=\; \int \frac{P(T,E)}{E} A(E) M(j,E) dE \tag{5}$$

(photons s^{-1} cm^5)

In this work we have also computed the *effective temperature* from the synthesized spectrum; i.e. the plasma temperature averaged over the emission as filtered and recorded through the instrument response,

$$T_{eff} = \frac{\int T(s) n_e(s) n_p(s) G(T(s))\ S(s)\ ds}{\int n_e(s) n_p(s) G(T(s))\ S(s)\ ds} \quad \text{(K)} \tag{6}$$

This figure is to be compared to the "temperature" measured by one-temperature fits to spectrally resolved observations, although it is not granted that a one temperature model gives a good χ^2 fit when the plasma is not isothermal, as it could be the case with loop's plasma.

For most of our spectral computations we have used the software environment ASAP (Analysis System for Astrophysical Plasmas; Maggio et al. 1994), written in IDL (Interactive Data Language) and designed for the analysis and presentation of models of astrophysical plasmas.

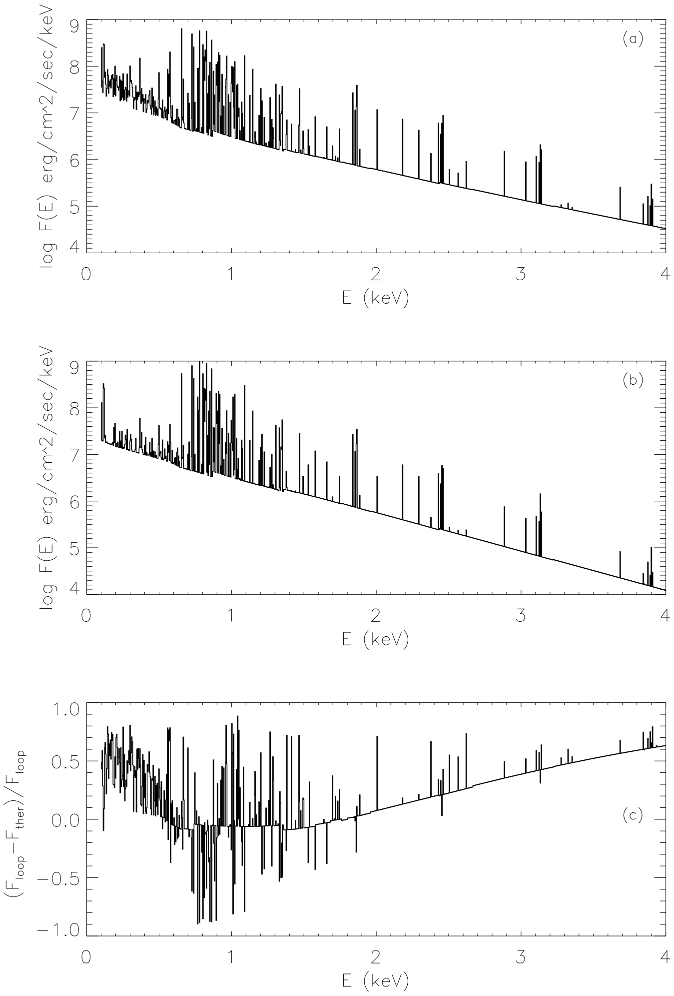

Fig. 1. (a) Spectrum synthesized from a loop model of semi-length 10^{10} cm and base pressure 30 dyn cm^{-2}, on a star with surface gravity $g = 3g_{\odot}$ and radius 3.3×10^{10} cm; (b) the spectrum emitted by an isothermal plasma yielding the same effective temperature (Eq. 6) and count rate through the ROSAT/PSPC as the loop of panel a; (c) the fractional difference between the two.

3. Results

3.1. Isothermal plasma vs loops plasma stratification

We have synthesized loop spectra and compared them with those of an isothermal plasma with the same luminosity and effective temperature in the ROSAT/PSPC (Trumper et al. 1991) passband. ROSAT/PSPC is a grazing-incidence X-ray telescope plus a proportional counter with spectral resolution $\Delta E/E \approx 0.45$ and effective area ~ 200 cm^2 at 1 keV. The response matrix and the effective area used here have been taken from the IRAF/PROS software package. Fig. 1 shows an example of spectra synthesized at high resolution within the $0.1 \div 4$ keV band (including therefore, the $0.1 \div 2.2$ keV ROSAT/PSPC passband) for a loop with semi-length 10^{10}cm and pressure 30 dyn cm^{-2}, on a star with gravity three times the solar one and radius 3.3×10^{10}cm. We have derived for this loop a maximum temperature

$T_{max} = 9.4 \times 10^6$ K and an effective temperature $T_{eff} = 6.0 \times 10^6$ K, when taking into account the ROSAT/PSPC spectral response. The lowest panel shows the fractional difference between the loop spectra and the isothermal spectrum at $T = T_{eff}$. The differences are indeed quite large in many parts of the spectrum. In fact, since a coronal loop contains a continuous distribution of plasma temperatures, there are lines and continuum contributions which should signal the non-isothermality of the corona. Lines of Si XIV (~ 2 keV), S XV (~ 2.45 keV), S XVI (~ 3.1 keV), Ca XVII and Ca XIX (~ 3.8 keV) in the loop spectra are more intense than in the isothermal spectrum. Moreover it is also possible, in principle, that the spectrum of a corona at high effective temperature contains also lower temperature lines such as the O VII (0.56 keV) line complex detectable with the Reflection Grating Spectrometer (RGS) on board XMM, and forming around a temperature of 2×10^6 K, and therefore very important to diagnose the lower corona. In particular the loop spectrum in Fig. 1 shows a strong O VII line, while the isothermal spectrum does not. Given the expected importance of the O VII line in a moderate temperature corona, evidently a more refined model than an isothermal plasma is required. The same reasoning as above applies to many other lines and complexes.

The spectral passbands of ASCA/SIS and of the European Photon Imaging Camera (EPIC) on board XMM extend to higher energies than the ROSAT/PSPC's ones and therefore we expect even larger discrepancies, as discussed in the following. Both the ASCA/SIS and the XMM/EPIC are based on CCD; the ASCA/SIS has an energy band ranging from 0.5 to 10 keV, and $\Delta E/E$ between 0.06 and 0.1 at 1 keV, depending on the read out noise (Tanaka 1990); the XMM/EPIC, to be flown around year 2000, will have an expected spectral resolution of 50 eV at 1 keV and 150 eV at 7 keV (Bignami et al. 1988), with an effective area of ≈ 2000 cm^2 at ~ 2 keV.

After having shown that a coronal loop spectrum is very different from that of an isothermal plasma, the next step is to ascertain if, and the extent to which, the non isothermality of a corona, even if dominated by one kind of loop, is indeed observable. To this end, a realistic simulation of an observation, apart from the loop model, requires the star's distance, the star's radius and the surface covering factor. We have considered models with the same loops as above ($L = 10^{10}$cm and $p_0 = 30$ dyn cm^{-2}) entirely covering the surface of a star, located at 13 *pc*, with radius 3.3×10^{10}cm, gravity $3g_\odot$, and observed with the ROSAT/PSPC over a $10^4 sec$ time lapse [1]. Figure 2a shows, in the left panel, the relevant spectrum in collected counts for this model corona, along with the spectrum for the isothermal corona of the same effective temperature, normalized so as to yield the same total number of photons, and in the right panel, the difference between the two spectra in units of standard deviation of Poisson noise.[2] Significant differences are evident.

We have repeated this computation also for ASCA/SIS and the XMM/EPIC, which have significantly higher resolutions, assuming the same physical conditions and observing time. Figure 2b shows the spectrum of the same corona, as seen by ASCA/SIS, along with the pertinent isothermal spectrum, and the difference between the two in the same units as above. [3] The effective temperatures is, for ASCA/SIS 6.7×10^6 K, and differences between loop and isothermal models are quite evident, especially below 0.7 keV, and in particular at the complex of unresolved lines of C VI, N VI-VII, Ca XI-XV and O VII ions in the range $0.4 \div 0.6$ keV.

Figure 2c yields the same loop spectrum as it would be detected by XMM/EPIC [4]. The effective temperature turns out practically the same as for the ROSAT/PSPC. Differences between the loop and the isothermal models are again evident, in particular we find remarkable differences for the complex at ~ 0.56 keV dominated by the O VII triplet, for that around ~ 0.8 keV dominated by Fe XVII, and for that at ~ 1.1 keV due to Ne X.

In Sect. 3.5 we present an example of the results obtained by fitting a real stellar spectrum, observed by ROSAT/PSPC, in terms of loop emitted spectra; we compare these results with the analogous one temperature component fitting.

3.2. Thermal conduction and loop spectra

Since the loop plasma thermal stratification is fundamental in making the loop spectrum different from that of an isothermal plasmas, it is also worth considering the role of heat conduction in determining the loop spectrum. In fact the specific heat conduction regime is fundamental in determining the loop plasma energy balance, its thermal stratification, and therefore the loop spectrum.

In CPS I and CPS II it has been shown that formulations of heat conduction more general than that of Spitzer and Harm (1953) are needed in the very diluted atmosphere of loops much higher than the pressure scale height. In

[1] Equivalent count rates could be obtained with appropriate different combinations of star's distance, surface coverage fraction and observing time.

[2] The standard deviation is the 1σ error on the number of counts in each instrument channel, computed in the Gaussian approximation.

[3] The response matrix and the effective area are taken from the ASCA calibration data base on the legacy.gsfc.nasa.gov anonymous FTP account.

[4] The response matrix and the effective area are taken from the ESA public archive at astro.estec.esa.nl.

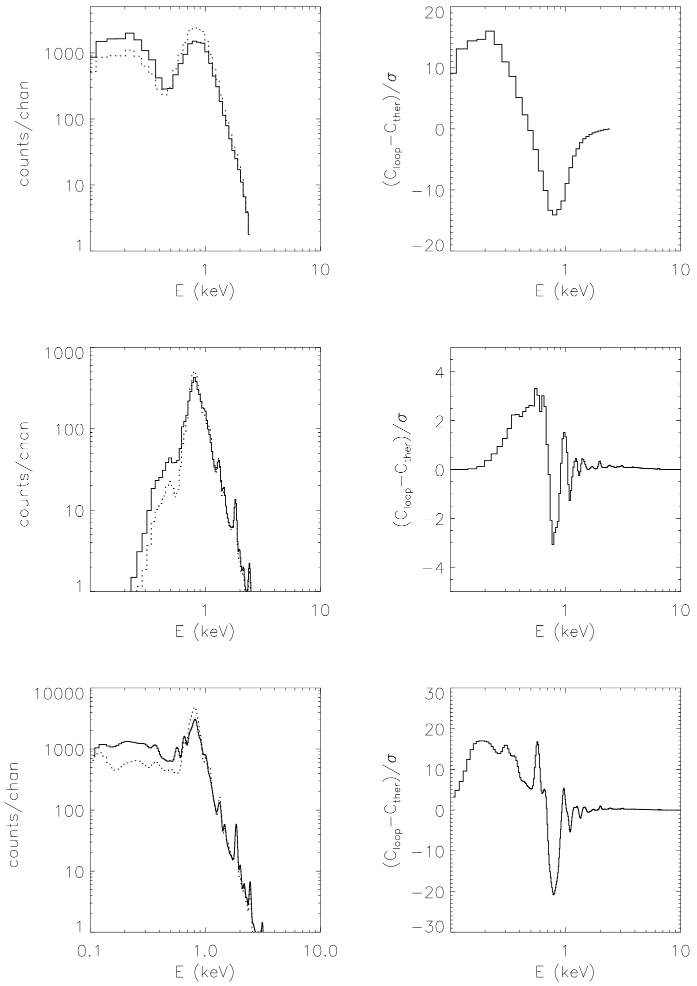

Fig. 2. In each row the left panel shows the same loop spectrum as in Fig.1 (solid line) and the spectrum of an isothermal plasma (dotted line) of the same effective temperature and count rate as seen through the specific instrument; the right panel shows the difference of the two spectra divided by one standard deviation of photon number Poisson noise, for each channel. The top row shows results for ROSAT/PSPC (effective temperature $T_{eff} = 5.96 \times 10^6$ K), the middle row for ASCA/SIS ($T_{eff} = 6.70 \times 10^6$ K), and the lower row for XMM/EPIC ($T_{eff} = 6 \times 10^6$ K).

particular it has been shown that loops in which limited free streaming conduction applies develop a temperature stratification and differential emission measure profiles very different from those predicted with models using Spitzer's conductivity, especially on high gravity stars.

While the conduction regime is important for an appropriate and general modeling of stellar coronae, one might wonder on the relevance of formulations other than Spitzer's one in modelling observed spectra. In the above two papers we have studied the physical conditions in coronal loops; here we synthesize the spectrum from such loops and show how they can differ from that of similar loops whose temperature stratification has been determined using only Spitzer's conductivity.

In order to show an example, we consider a representative loop structure, with $p_0 = 0.3$ dyn cm^{-2} and $L = 2 \times 10^{10}$ cm on a star with surface gravity $g = 10\, g_{\odot}$, and radius 9.94×10^9 cm (a star similar to Proxima Centauri): in Fig. 3a we compare the spectra synthesized using only the Spitzer conduction regime with that obtained allowing for the limited free-streaming conduction regime (Mannheimer 1977), and in Fig. 3b the difference between these spectra. This loop is, among the several ones with very large deviations from Spitzer's conduction regime which we have studied in CPS I and CPS II, the one with the highest pressure, therefore one of the most easily observable, and ultimately a good case to prove the irrelevance of thermal conduction mechanisms other than Spitzer's one.

In general, whenever there are conditions conducive to limited free-streaming conduction, the loop contains hotter plasma, and therefore the spectrum extends to higher energy, and is richer of high temperature lines, than one would

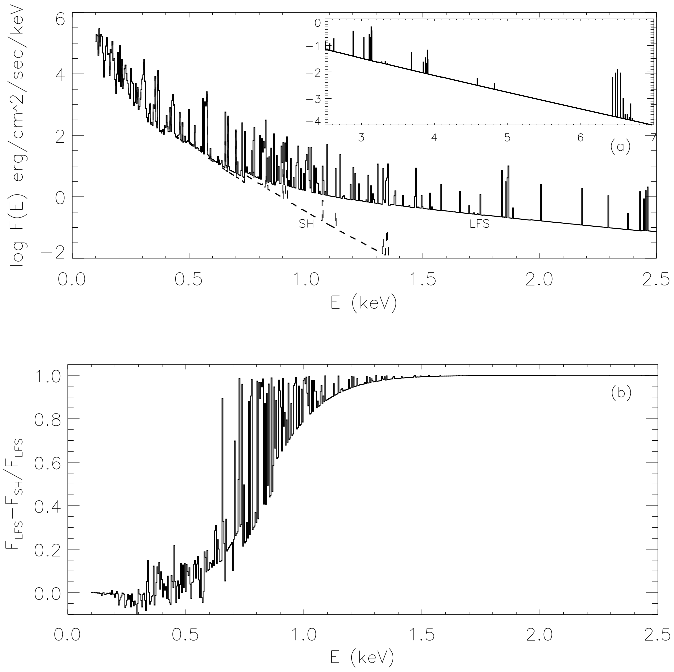

Fig. 3. Panel (a) shows the spectra vs. photon energy synthesized from models of loop using Spitzer (dashed line) and limited free-streaming (solid line) thermal flux formulation, for a loop with base pressure $p_0 = 0.3$ dyn cm^{-2} and semi-length $L = 2 \times 10^{10}$ cm on a star with surface gravity $g = 10 g_{\odot}$ and radius 9.94×10^9 cm. The inset in (a) shows the spectra in the range $2.5 \div 7$ keV, the dashed line falling well below the abscissa axis. Panel (b) shows the fractional difference between the two spectra vs. photon energy.

instead obtain only on the basis of Spitzer conduction, as shown in the inset of Fig. 3a (cf. also CPS II). In fact, at high photon energy we find several complexes of lines, even though at a low emission level, not present in the spectrum synthesized with the traditional loop model: cf. for instance the complex of Fe XXV formed in the range $\sim 6.4 \div 6.7$ keV, and that of Ca (XVII $\div$ XIX) at 3.8 keV in the inset of Fig. 3a. There the spectrum computed with the Spitzer conductivity is so weak as to fall below the abscissa axis. At lower energies we find the complex of S XV at ~ 2.45 keV, and at ~ 2.2 keV the line of Si XIII. Moreover, remarkable differences are found also in the lines at ~ 0.78 keV (Fe XVIII + O VIII), at ~ 0.90 keV (Fe XVIII) and at ~ 1.15 keV (Fe XIX).

Due to the extreme dilution of the plasma in the regions where non-Spitzer conduction dominate, we might ask whether a description of conduction more appropriate than Spitzer's is necessary to compare observations with models. To this end we have considered realistic observing conditions (as discussed in the following in more detail) and we have computed the expected count rate and effective temperature in the ROSAT/PSPC and XMM/EPIC passbands, and we have found that some coronae entirely made of identical loops in non-local or free-streaming regime could emit enough X-ray radiation to be detected, in principle, at good S/N values, either with ROSAT/PSPC or with XMM/EPIC. We have then evaluated the spectra for these coronae as observed with both instruments, to identify possible tracers of the physical conditions of the coronal plasma. In Fig. 4 we show the XMM/EPIC spectra (solid histograms) vs. photon energy for a corona made of loops with $p_0 = 1$ dyn cm^{-2} and $L = 2 \times 10^{10}$ cm and completely covering a star with gravity $10 g_{\odot}$, radius 9.94×10^9 cm at distance 1.3 pc and observed for $10^5 sec$. They are obtained with the model which allows for limited free-streaming thermal conduction, and with a model using only Spitzer conduction. In the same figure we report the S/N ratio vs photon energy (dotted lines) for errors entirely due to photon number fluctuations, for the limited free-streaming corona. The vertical dashed line in the figure marks the highest value of photon energy for which $S/N \geq 1$ in the energy bin. Although the two spectra in Fig. 4 are quite different at energies ≥ 1 keV, the S/N ratio decreases with energy, thus making it quite difficult to detect the high energy part of the spectrum, where the differences between the two spectra become very important. It is even harder to detect differences in the spectra collected with ROSAT/PSPC. We conclude that the outer layers of the loop atmospheres, where we expect deviations from Spitzer's conductivity, should contribute very little to detectable spectra, even if observing with XMM/EPIC.

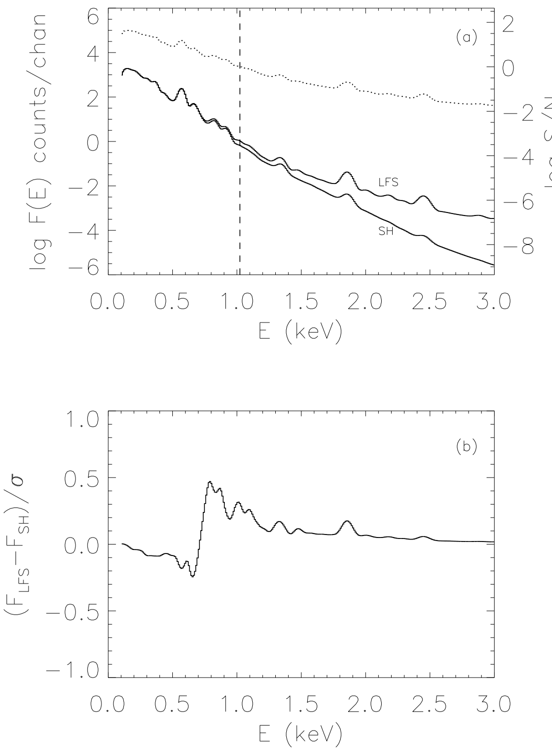

Fig. 4. (a) Spectrum vs photon energy (solid curves) of a corona made of loops with $L = 2 \times 10^{10}$ cm and $p_0 = 1$ dyn cm^{-2} entirely covering a star with $g = 10g_\odot$, $R = 9.94 \times 10^9$ cm, at a distance of 1.3 pc and observed with XMM/EPIC for 10^5 sec. The loops are either modeled with Spitzer conduction (SH) or with the appropriate model using limited free-streaming conduction (LFS). The dotted curve shows the signal to noise ratio (S/N) for the LFS corona. The dashed vertical line marks the highest photon energy value for which $S/N \geq 1$. Panel (b) shows the difference between the two spectra divided by one standard deviation of photon number Poisson noise (cf. Sect. 4.1).

3.3. Loops with widening cross section

Solar X-ray observations with Skylab/S054 (Vaiana and Rosner 1978) and more recently from the Soft X-ray Telescope on board Yohkoh and from the Normal Incidence X-ray Telescope (Tsuneta & Lemen 1993; Uchida 1993; Golub 1993), have shown that small loops typically have a constant cross section. To be more specific, Rosner and Vaiana (1977) showed, on the basis of EUV observations obtained with S055/Skylab, that the magnetic flux tubes undergo a rapid change of cross section at the height where the plasma is at a temperature of a few hundred thousand degrees, i.e. in the transition region; therefore the loops most likely expand in the transition region but then their section changes, at most, very slowly in corona. The X-ray observations (Vaiana, Krieger and Timothy, 1973; Vaiana and Rosner, 1978) have shown that very long loops typically are characterized by a gradual and significant expansion of their cross section, reaching a maximum at the apex.

It should be considered that a cross section increase along the loop implies a larger loop's volume near the top of the structure, where the temperature is maximum. Therefore loop widening could be important either to determine the spectrum emitted by the loop and/or the observability of those coronae which are mostly composed of very long and tenuous structures. The influence of widening loop cross section has already been evaluated in previous papers (Vesecky et al. 1979, Serio et al. 1981, Stern et al. 1986, Schrijver et al. 1989, Ottman 1993). Here we concentrate on studying how loop widening influences the spectrum.

We model loops whose cross sectional area $S(s)$ expands in the corona according to:

$$S(s) = S_0 \left(1 + \frac{h}{R_\star}\right)^{\varepsilon} \tag{7}$$

where S_0 is the area at the loop footpoint, h is the height above the star surface, $R_\star$ the stellar radius and ε the expansion parameter. In order to help comparison with previous works, most notably those based on the model of

Vesecky et al. (1979), we shall also report the values of $\Gamma = S_{apex}/S_0$, namely the area expansion factor between the apex and the footpoints of the loop (depending also on the loop length).

In accordance with Vesecky et al. (1979) and Serio et al. (1981) we find slightly lower maximum temperature values, and slightly larger differential emission measure values, for larger ε, i.e. for faster widening of loop cross section with height. The effect on the maximum temperature is not strong, amounting, at most, to a decrease of maximum temperature by a factor of 1.4 for a loop with $L = 5 \times 10^{10}$ cm, $p_0 = 30$ dyn cm^{-2} and $\varepsilon = 2$ ($\Gamma = 15$) on a star with gravity 10 $g_\odot$ and radius 9.94×10^9 cm. For the same model, the corresponding increase of the differential emission measure reaches about a factor 10 near the loop top. Note that the value $\varepsilon = 2$, in practice, accounts for a radial expansion.

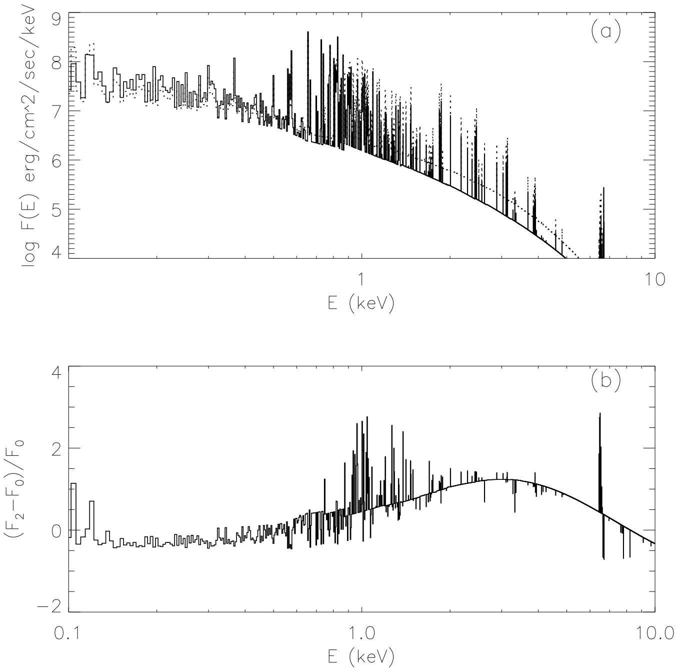

Fig. 5. (a) Emitted spectra vs photon energy for a loop characterized by $L = 5 \times 10^{10}$ cm, $p_0 = 30$ dyn cm^{-2} on a star with gravity $10 g_\odot$ and radius 9.94×10^9 cm with different expansion exponent $\varepsilon = 0$ ($\Gamma = 1$, solid) and $\varepsilon = 2$ ($\Gamma = 15$, dotted) normalized to the same flux in the $0.1 \div 10$ keV band. Panel b shows the fractional difference between the two spectra.

We have computed the spectra for the loop model described above and we have normalized them to the same flux in the $0.1 \div 10$ keV band by adjusting their respective star's surface filling factors. These sample spectra and their fractional difference, for our two extreme cases $\varepsilon = 0$ and $\varepsilon = 2$ (i.e. $\Gamma = 1$ and $\Gamma = 15$), are shown in Fig. 5a and 5b respectively. Loop widening produces a spectrum generally harder than that emitted from loops with constant cross-section. In particular the largest differences are present in the $0.8 \div 2$ keV range where there are important lines for the density diagnostic of coronal plasmas, such as the complex of Fe XX-XXIII at ~ 1 keV. Large differences are also present for the iron lines at ~ 6.5 keV. Moreover the continuum in the $1 \div 7$ keV band is higher than for the loop with constant section. Some of these effects have been already studied by Schrijver et al. (1989) in their analysis of the spectra of some active stars observed with EXOSAT/TGS (see Mewe 1993 for a detailed review).

We have also evaluated the observability of these effects with different instruments. For all the cases reported in Table 1, we have analyzed the predicted spectra taking into account the spectral response of the ROSAT/PSPC, of ASCA/SIS and of XMM/EPIC. We have normalized all the PSPC spectra to a total of 10^4 photons (typical of several good ROSAT observations of coronal sources). Then, we have fixed the combination of exposure time, stellar surface covering factor and star's distance according to the normalization of the PSPC spectra, and we have derived the relevant spectra also for ASCA/SIS and XMM/EPIC. For each case we have computed the difference between the spectra for constant and variable cross-section in each energy bin, divided by one standard deviation due to Poisson noise, as defined in Sect. 4.1. We have also computed the effective temperature (Eq. 6) for the three instruments and we have verified that it generally increases with the expansion parameter for the loop models considered.

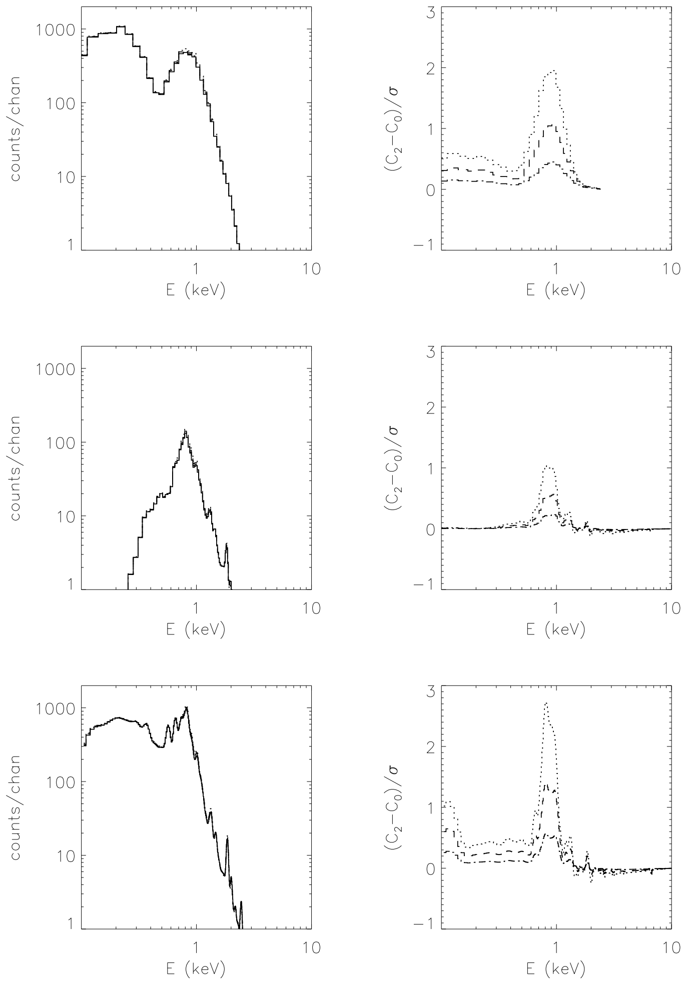

Fig. 6. Spectra synthesized for coronal models entirely made with loop as of Fig. 5 but for constant (solid line) and variable cross-section. In the latter case the figure shows the spectra for $\varepsilon = 0.55$ ($\Gamma = 2$) (dashed dotted line), 1.2 ($\Gamma = 5$) (dashed line) and 2 ($\Gamma = 15$) (dotted line) respectively. The source's and the observation's features are fixed to yield a total number of photons of 10^4 with the ROSAT/PSPC. In each row the left panel shows the spectra, and the right panel their difference divided by one standard deviation of Poisson noise, for each channel. The results pertain to observations with ROSAT/PSPC (top row), ASCA/SIS (middle row), and XMM/EPIC (bottom row).

As for the observability of the expansion effects, we have found a large variety of results. In Fig. 6 we show the results obtained for the same loop as in Fig. 5 but for three values of expansion parameter $\varepsilon = 0.55, 1.2, 2$ (i.e. $\Gamma = 2, 5, 15$), with respect to the spectrum computed for constant cross-section. The differences due to the expansion effects for this loop model are the most extreme ones, among all the cases explored. The spectra predicted for ROSAT/PSPC are significantly different at photon energies of 1 keV and the differences increase with ε because the effective temperature also increases from $T_{eff} = 5.1 \times 10^6$ K for the loop with uniform cross-section to $T_{eff} = 7.5 \times 10^6$ K for $\varepsilon = 2$ ($\Gamma = 15$). A similar result holds for XMM/EPIC, while the differences, although present, are less significant in the case of the ASCA/SIS, because of the specific characteristics of this instrument (Sect. 3.1). Of course, such differences would be more significant with even better statistics. Therefore we concluse that loop expansion should be taken into account in the interpretation of stellar coronal emission, although its influence can be mixed with that of the other physical effects.

We have also verified that the presence of a heat transport regime different from Spitzer's one does not influence the above results by a detectable amount.

3.4. Multi-Loop Models

In the preceding part of the paper we have examined several loop features potentially conducive to detectable effects in the observed spectra. A typical feature of the solar corona is, on the other hand, the simultaneous presence of several kinds of loops with different characteristics, as vividly shown by decades of soft X-ray observations of the Sun. An accurate study of the effects of loop multiplicity and the extent to which such multiplicity is detectable, depending on the instrument characteristics, is beyond the limits of the present paper and will be tackled in a future work. Here, however, we just show how the presence of loops containing relatively dense plasma can easily dominate the emission from tenuous loops.

We consider a system composed of several identical active region-like loops (ARL), i.e. compact and dense, and several identical large scale structure-like loops (LSS), i.e. long and tenuous, with different fractions of the star's surface covered by the two. We have synthesized the spectra for this model of corona assuming a typical exposure time of $10^4 sec$ and computed the expected ROSAT/PSPC spectrum, considering statistical noise and neglecting background contamination. We have taken, as an example of ARL, the one used by Reale et al. (1988) as the initial condition of a flare observed on Proxima Cen with the *Einstein*/IPC ($L = 7 \times 10^9$ cm, $p_0 = 10$ dyn cm^{-2}). The LSS model considered here has $L = 5 \times 10^{10}$ cm and $p_0 = 1$ dyn cm^{-2} and is also characterized by strong deviations from the Spitzer's conduction regime being in limited free-streaming conditions. The parameters characterizing the two loops are presented also in Table 2, along with their effective temperature in the ROSAT/PSPC band.

Table 2. Loop parameters and their effective temperatures.

L (cm)	p_0 (dyn cm^{-2})	T_{max} (10^6 K)	T_{eff} (10^6 K)
7×10^9	10	5.52	2.71
5×10^{10}	1	11.8	0.99

We have found that the ARL contribution is dominant almost by two orders of magnitude with respect to the other one if the two kinds of loops cover equal fractions of the stellar surface. Therefore, even a very small fraction of the stellar surface (e.g. a few $\times$ 10^{-2}) covered by compact loops filled with dense plasma determines the spectrum of the star. We postpone a more detailed analysis, including a fitting of the synthesized spectra by means of one or two temperature spectra of isothermal components, to a future work.

3.5. Fitting real data

Although ROSAT/PSPC data have been available since few years, in our knowledge only one attempt of spectral analysis with loop models has been performed so far (Ottmann 1993). In the present work, we want to show that a loop model may yield a significant improvement in the spectral fitting of real data, with respect to an isothermal model. In Fig. 7 we show the spectrum of the giant star ι Vir, already analyzed with isothermal plasma plasma models by Maggio et al. (1994). In the figure we also show two best-fit models: an isothermal best-fit model which, however, fails to provide a good fit to the data, and a loop model. In Table 3 we report the model parameters and the best-fit χ^2 obtained with the above two models and with two more loop models, selected for comparison: one within the 68 % confidence level and the other outside it, all three with the same effective temperature $T_{eff} = 6.2 \times 10^6$ K. The confidence levels, has been computed according to Avni (1976). Note that two of the loop models (namely those within the 68 % confidence region) provide acceptable fits to the data, but not the third one. This result demonstrates that (1) the available data discriminate between an isothermal model and a loop model, (2) that loop models can provide useful diagnostics of the coronal plasma conditions and (3) that the effective temperature alone (or the isothermal plasma temperature) provide a very limited insight on data and an accurate fitting of data is in order, as presented in Paper II and following ones. An extensive and systematic analysis of X-ray observations is outside the scope of this paper and will be presented in a forthcoming set of works, which include the results of Fig. 7.

Table 3. Fitting results to the ι Vir ROSAT/PSPC spectrum

Loop Models ($T_{eff} = 6.2 \times 10^6$ K)				
L cm	p_0 dyn cm^{-2}	T_{max} 10^7 K	χ^2_{red} (23 d.o.f.)	Remarks
2.5×10^{11}	3.2	1.3	0.77	Best-fit model
6.3×10^{11}	2.0	1.5	0.96	
1.0×10^{10}	40.0	1.0	1.43	

Isothermal Model	
T 10^6 K	χ^2_{red} (24 d.o.f.)
3.9	7.9

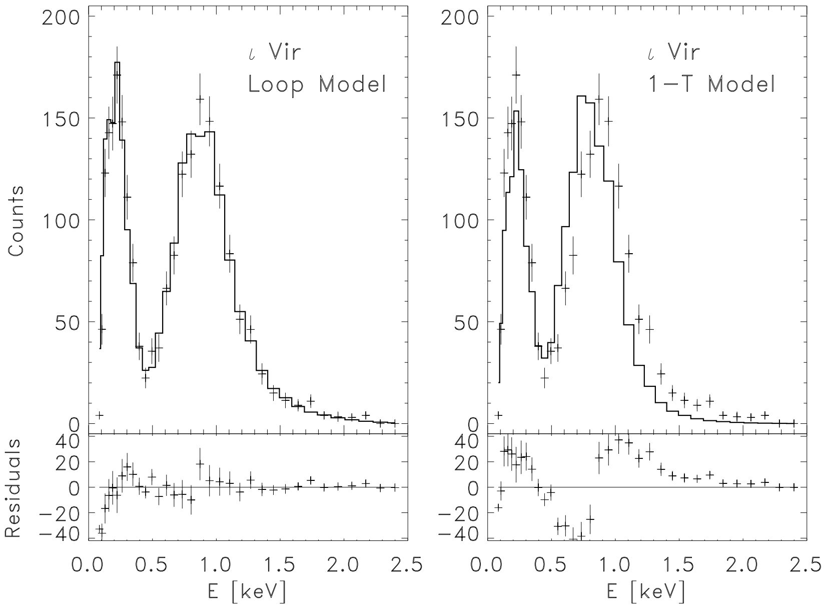

Fig. 7. ROSAT PSPC spectrum of the F6III star ι Vir, fitted with a loop model (left panel) having plasma base pressure $p_0 = 3.2$ dyn cm^{-2} and loop semi-length $L = 2.5 \times 10^{11}$ cm, and with an isothermal model (right panel) with $T = 0.34$ keV. While the loop model provide an acceptable fit to the data ($\chi^2_{red} = 0.8$), the isothermal model does not ($\chi^2_{red} = 7.9$).

4. Discussion and conclusions

In this paper we have studied several aspects of coronal loop physics, in the scope of establishing their influence on coronal spectra and understanding their role in the interpretation of coronal observations in terms of coronal loop models.

As a first step we have compared two very different kinds of coronal models: the isothermal plasma model and a model based on coronal loops. The comparison between the spectra computed according to the two models shows remarkable differences and, in particular, the presence of spectral features emitted by the loop which indicate the presence of plasma at temperatures both higher and lower than the effective temperature. Such differences can be important in observations, as we have shown folding the predicted spectra through the instrumental response of ROSAT/PSPC, ASCA/SIS and XMM/EPIC, and considering realistic observing conditions. Therefore, we expect an increasing difficulty of fitting coronal observations with single temperature isothermal models as the quality of spectral data improves. Adoption of two isothermal plasma components might fix somehow, and limitedly, the problem but certainly does not address its physical implication. In particular, although two temperature loops can give a fitting to ROSAT/PSPC an ASCA/SIS spectra typically equivalent, the physical insight is much less than that obtainable with loops which we know are the building block of the corona (at least in the spatial resolved case, the Sun).

The next step has been to study whether some characteristics (namely conduction regime, loop expansion or loop multiplicity), known to govern loop physics, are important to model observable features. With this scope in mind we have first studied the effect of thermal flux regime on the emitted coronal spectrum and shown that, albeit coronal loop structures with large deviations from Spitzer conduction regime can have spectra very different from those predicted with Spitzer conduction, the differences will not be observable even with EPIC/XMM. Most of the emission originates from plasma below the pressure scale height, not affected both by the limited free-streaming conduction.

As for loops entirely in Spitzer regime - which, on the basis of the results on heat conduction, are the ones we plan to use to interpret the X-ray coronal emission - we have studied the difference in their spectra brought by a change of cross section along the loop, synthesized taking into account the instrumental response of ROSAT/PSPC, of ASCA/SIS and of EPIC/XMM. We have found a wide variety of cases, for a total number of 10^4 photons collected by ROSAT/PSPC, ranging from coronal spectra where loop widening makes no difference to others where spectra show sizable differences. Two effects compete to determine the loop effective temperature: the area expansion lowers the maximun (apex) temperature but, one the other hand, increases the emission measure at higher temperatures. For all the cases we have studied, namely loops shorter than 10^{11} cm, we have found that the second effect prevails and, in fact, effective temperature increases with the expansion parameter. We cannot exclude, however, a different result for even longer loops. Since the above results depend quantitatively on several factors, including the instrument's sensitivity, the spectral resolution, the total number of collected photons (there are a few sources yielding even more photons than assumed above), and probably also the expansion law considered, we can conclude that a project aimed at generality should also consider the possibility of loop widening when fitting coronal spectra.

We have then briefly evaluated how the presence of loops with different physical and geometrical conditions influence the observed spectra. Already for very simple coronal models made of only two kinds of loops, we have found that the spectra emitted by active region loops overwhelm those emitted by tenuous and long loops by almost two orders of magnitude, when equal fractions of the stellar surface are covered by their footpoints. Active region loops dominate even when they cover a few percent of the stellar surface. Therefore the emission of dense and hot loops typical of active regions can easily dominate stellar emission, particularly in the most active and luminous stars.

Finally we have presented an example of fitting real data extracted from the results of a forthcoming paper Maggio et al. (1995). All the work reported in this paper has been aimed at setting a scenario and clarifying the role of several factors entering loop modeling. A parallel work (Paper II) deals with spectral fittings made with simulated coronal loop spectra. Future work shall deal in further detail with some of the aspects here just touched upon, with fitting techniques and, eventually, with applications to real data of those methods which will have been proved reliable and reasonably tested.

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