Nonplanar Dust-Ion Acoustic Solitary Waves in Warm Plasma With Superthermal Electrons

Parvin Eslami, Marzieh Mottaghizadeh, and Hamid R. Pakzad

***Abstract*— Using the reductive perturbation technique, a cylindrical/spherical Korteweg–de Vries (KdV) equation is derived for dust-ion acoustic solitary wave (DIASW) in an unmagnetized dusty plasma, whose constituents are adiabatic ion fluid, superthermal electrons, and negatively charged static dust particles. The solution of modified KdV equation in nonplanar geometry is numerically analyzed. The change of the DIASW structure due to the effect of the geometry, superthermal parameter, dust density, and ion temperature is investigated by numerical calculation of the cylindrical/spherical KdV equation.**

***Index Terms*— Dust-ion-acoustic solitons, dusty plasmas, nonplanar geometry, reductive perturbation method, superthermal electrons.**

I. INTRODUCTION

DUST is ubiquitous in most space and astrophysical plasma systems, such as molecular clouds, protostellar disks, interstellar and circumstellar clouds, asteroid zones, planetary atmospheres, interstellar media, cometary tails, nebula, earth's ionosphere, and so on [1]–[4]. Dust particles are not neutral, but are charged either negatively or positively depending on the ambient plasma environments [5]–[7]. One of the important electrostatic dust-associated waves, which exist in unmagnetized dusty plasmas, is the low-frequency dust-ion acoustic waves (DIAWs). Shukla and Silin [8] have first theoretically shown that due to the conservation of equilibrium charge density $n_{e0} + Z_d n_{d0} = n_{i0}$, and the strong inequality $n_{e0} \ll n_{i0}$ [where n_{e0}, n_{d0}, and n_{i0} are, respectively, electron, dust, and ion number density at equilibrium, Z_d is the number of electrons residing onto the dust grain surface, and e is the magnitude of the electronic charge] a negatively dusty plasma supports low-frequency DIAWs with phase speed much smaller (larger) than the electron (ion) thermal speed. The DIAWs have also been observed in laboratory experiments [9], [10]. Note that the DIAWs significantly differ from the dust acoustic (DA) waves in which the dust dynamics must be considered, i.e., the inertia is provided by the dust particle mass, and the restoring force comes from the pressures of inertialess electrons and ions [11]–[13]. The linear properties of the DIAWs in dusty plasmas are now well understood from both theoretical and experimental points of view [6], [8], [10], [14]. The nonlinear features of the DIAWs have also received a great deal of interest in understanding the basic properties of localized electrostatic perturbations in space and laboratory dusty plasmas [6], [10], [18]–[21]. The DIA solitary waves (DIASWs) have also been investigated [15]–[19], but the works [16], [19]–[21] are valid only for an unmagnetized dusty plasma with cold ions and isothermal (Maxwellian) electrons. Recently, Mamun [22] has investigated the basic properties of 1-D DIASWs in an unmagnetized adiabatic dusty plasma, which contains noninertial adiabatic electrons, inertial adiabatic ions, and negatively charged static dust. More recently, some authors studied DA and DIA solitary and shock structures in a dusty plasma with electrons following a q-nonextensive distribution [23]–[25]. Numerous observations of space plasmas [26], [27] indicate clearly the presence of superthermal electron and ion structures as ubiquitous in a variety of astrophysical plasma environments. Plasmas with an excess of superthermal (non-Maxwellian) electrons are generally characterized by a long tail in the high energy region. To model such space plasmas, generalized Lorentzian of k distribution has been found to be appropriate rather than the Maxwellian distribution [28]–[31]. Kappa distribution has been used [32]–[36] in studying the effect of Landau damping on various plasma modes. Superthermal plasma behavior was observed in various experimental plasma contexts, such as laser matter interactions or plasma turbulence [37]. At very large values of the spectral index k, the velocity distribution function approaches a Maxwellian distribution, while for low values of k, they represent a hard spectrum with a strong non-Maxwellian tail having a power law form at high speeds. Recently, some researches have been done on electron, ion, dust, and DIASWs using superthermal distribution for ions and/or electrons [35], [38]–[41]. Theoretical researches show that the properties of SWs in bounded nonplanar geometry are very different from those in unbounded planar geometry [42]. More recently, the effects of superthermal electrons on DIASWs in an adiabatic dusty plasma containing positively and negatively charged dust has been investigated in [43]. To study the DIAWs in the nonplanar geometry with radial symmetry, we consider an unmagnetized plasma whose constituents are stationary dust grains, cold inertial ions, and superthermal electrons.We have employed the reductive perturbation method (RPM) to derive the dynamical equations

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P. Eslami is with the Department of Physics, Ferdowsi University of Mashhad, Mashhad, Iran (e-mail: eslami@um.ac.ir).

M. Mottaghizadeh is with the Department of Physics, Mashhad Branch, Islamic Azad University, Mashhad, Iran (e-mail: m_mottaghizadeh@yahoo.com).

H. R. Pakzad is with the Department of Physics, Bojnourd Branch, Islamic Azad University, Bojnourd, Iran (e-mail: pakzad@bojnourdiau.ac.ir).

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for the nonlinear propagation of the electrostatic waves in dusty plasma under consideration. The organization of this paper is as follows. In Section II, the basic equations are given. We have derived the cylindrical/spherical Korteweg–de Vries (KdV) equation using RPM in Section III. In Section IV, the effect of the geometry, superthermal parameter, dust density, and ion temperature on DIASW structures is considered. Finally, conclusions are drawn in Section V.

II. THEORETICAL MODEL AND BASIC EQUATION

We consider an unmagnetized dusty plasma system consisting of adiabatic ion fluid, superthermal distributed electrons, and static negatively charged dust particles. The nonlinear dynamics of the DIAWs in such a dusty plasma system in nonplanar cylindrical and spherical geometries is governed by [44]

$$\frac{\partial n_i}{\partial t} + \frac{1}{r^\nu}\frac{\partial}{\partial r}(r^\nu n_i u_i) = 0 \tag{1}$$

$$\frac{\partial u_i}{\partial t} + u_i\frac{\partial u_i}{\partial r} = -\frac{\partial \phi}{\partial r}\phi - \frac{\sigma}{n_i}\frac{\partial p_i}{\partial r} \tag{2}$$

$$\frac{\partial p_i}{\partial t} + u_i\frac{\partial p_i}{\partial r} + 3p_i\frac{1}{r^\nu}\frac{\partial}{\partial r}(r^\upsilon u_i) = 0 \tag{3}$$

$$\frac{1}{r^\nu}\frac{\partial}{\partial r}(r^\upsilon\frac{\partial \phi}{\partial r}) = \mu n_e - n_i + 1 - \mu \tag{4}$$

where $\nu = 0$, for 1-D geometry and $\nu = 1(2)$ for a nonplanar cylindrical (spherical) geometry. The variables ion number density (n_i), ion fluid velocity (u_i), ion thermal pressure $(\mathrm{p_i})$, and the electrostatic potential φ are normalized by the ion equilibrium density n_{i0}, effective ion acoustic velocity $\mathrm{C_i} = \sqrt{\mathrm{T_e/m_i}}$, $n_{i0}T_i$, and the quantity $\mathrm{T_e}/e$, respectively. The space and time variables are normalized to the Debye radius $\lambda_{De} = \sqrt{T_e/4\pi n_{i0}e^2}$ and the reciprocal ion plasma frequency $\omega_{pi}^{-1} = \sqrt{m_i/4\pi n_{i0}e^2}$, respectively. We have set $\mu = n_{e0}/n_{i0}$ and $\sigma = T_i/T_e$, in which T_e and $\mathrm{T_i}$ are the electron and the ion fluid temperature, respectively. It may be noted that $Z_d n_{d0}/n_{e0} = (1-\mu)/\mu$, we set $Z_d = 1$. The electrons are assumed to be superthermally distributed; consequently, the normalized number density of electron is given by

$$n_e = \left(1 - \frac{\phi}{k - 1/2}\right)^{-k-1/2} \tag{5}$$

where k is a real parameter measuring deviation from Maxwellian equilibrium (recovered for k infinite), the normalization has been provided for any value of the k >1/2 [44], [45].

III. DERIVATION OF THE NONPLANAR KdV EQUATION

In what follows we will apply the standard reductive perturbation technique to (1)–(5) to obtain the modified KdV equation. According to this method, we introduce the stretched space-time coordinates τ and ξ through the relations [46]

$$\tau = \varepsilon^{3/2}t, \xi = \varepsilon^{1/2}(r - V_0 t) \tag{6}$$

where ε is a small parameter and V_0 is the wave phase velocity. Now, we expand each variable in powers of ε as

$$n_i = 1 + \varepsilon n_i^{(1)} + \varepsilon^2 n_i^{(2)} + \varepsilon^3 n_i^{(3)} + \ldots \tag{7}$$

$$u_i = \varepsilon u_i^{(1)} + \varepsilon^2 u_i^{(2)} + \varepsilon^3 u_i^{(3)} + \ldots \tag{8}$$

$$p_i = 1 + \varepsilon p_i^{(1)} + \varepsilon^2 p_i^{(2)} + \varepsilon^3 p_i^{(3)} + \ldots \tag{9}$$

$$\varphi = \varepsilon\varphi^{(1)} + \varepsilon^2\varphi^{(2)} + \varepsilon^3\varphi^{(3)} + \ldots . \tag{10}$$

On substituting (7)–(10) into (1), using (6) and collecting the terms in the different powers of ε, the cylindrical and spherical KdV equation is derived

$$\frac{\partial \varphi^{(1)}}{\partial \tau} + \frac{\nu\,\varphi^{(1)}}{2\tau} + \mathrm{A}\varphi^{(1)}\frac{\partial \varphi^{(1)}}{\partial \xi} + \mathrm{B}\frac{\partial^3 \varphi^{(1)}}{\partial \xi^3} = 0 \tag{11}$$

where coefficients of A and B are

$$A = \frac{1}{V_0}\left(\frac{3}{2} + \frac{6\sigma}{(V_0^2 - 3\sigma)} - \mu\frac{(2k+1)(2k+3)(V_0^2 - 3\sigma)^2}{2(2k-1)^2}\right)$$
$$B = \frac{(V_0^2 - 3\sigma)^2}{2V_0} \tag{12}$$

where A and B are the coefficients of nonlinearity and dispersion, respectively. If we put $\nu = 0$ in (11), we obtain the planar KdV equation $\nu = 1, 2$ corresponds to the KdV equations in the cylindrical and spherical geometries.

IV. NUMERICAL RESULTS AND DISCUSSION

In this section, we present numerical solutions of (11) using a standard fourth-order Runge–Kutta scheme [46], the two-level finite difference approximation method [47], and study the geometrical effects on time-dependent DIASWs in dusty plasma under consideration. Assuming $\nu = 0$, a stationary propagation of the DIASW governed by (11) has the following form:

$$\varphi^{(1)} = \varphi_m \sec h^2\left(\frac{\xi - u_0\tau}{\Delta}\right) \tag{13}$$

where $\phi_m = 3u_0/A$ is the amplitude, $\Delta = \sqrt{4B/u_0}$ is the width (the full width at half maximum in the soliton profile) of the SWs, and u_0 is a constant velocity normalized to C_i. The initial condition that we have used in all our numerical results is the form of (13) at $\tau = -1.6$ (at this stage the geometry effect is weaker; hence, we can take this stage as the initial stage of evolution). The results are shown in Figs. 1–7. Figs. 1 and 2 show that how the superthermal parameter k affects DIA solitons in cylindrical and spherical geometries. In Fig. 1, the cylindrical DIASWs have been plotted at $\tau = -31.6, -11.6$, for $\sigma = 0.8$, $\mu = 0.9$ and different values of k. Fig. 1 shows that amplitude increases with increase in τ as well as the value of k. Furthermore, We see that a small value of k and thus an increase in superthermality (decreasing k) increases the value of speed of DIASWs. It was mentioned that the distribution of electrons approaches the Maxwellian as $k \to \infty$. Fig. 2 shows the result for $\nu = 2$; the rest of the parameters are the same as those in Fig. 1. It is seen that the effect of superthermality in the plasma is more pronounced in the spherical geometry. Depending whether coefficient of nonlinearity A is positive or negative, Fig. 3 shows that the DIASWs may exhibit

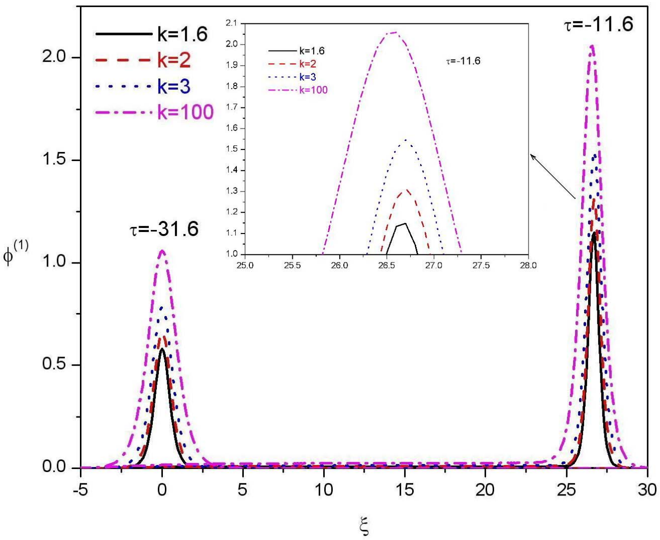

Fig. 1. Time evolution of cylindrical SWs: $\varphi^{(1)}$ versus ξ at $\tau = -1.6, -11.6$ for different values of k, with $\sigma = 0.8$, $\mu = 0.9$.

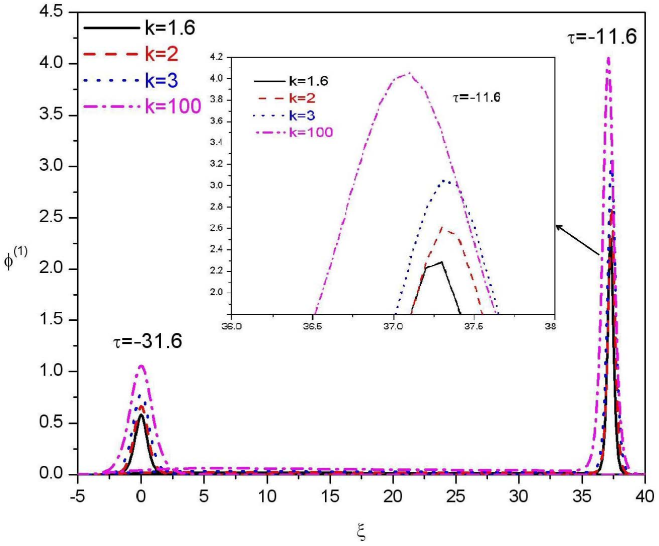

Fig. 2. Time evolution of spherical SWs: $\varphi^{(1)}$versus ξ at $\tau = -1.6, -11.6$ for different values of k, with $\sigma = 0.8$, $\mu = 0.9$.

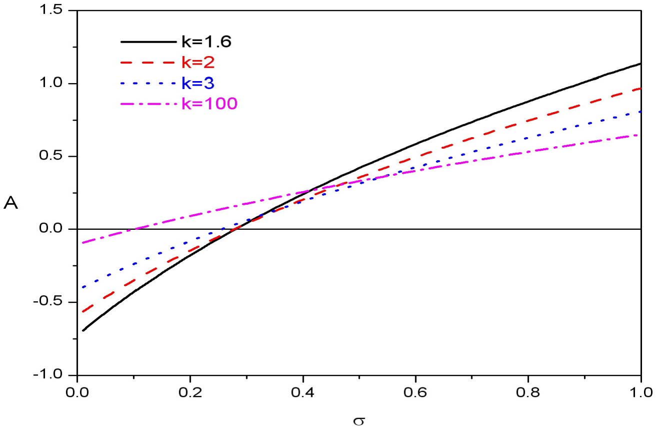

Fig. 3. Variation of the coefficient A versus σ for different values k with $\upsilon = 1$ and $\mu = 0.3$.

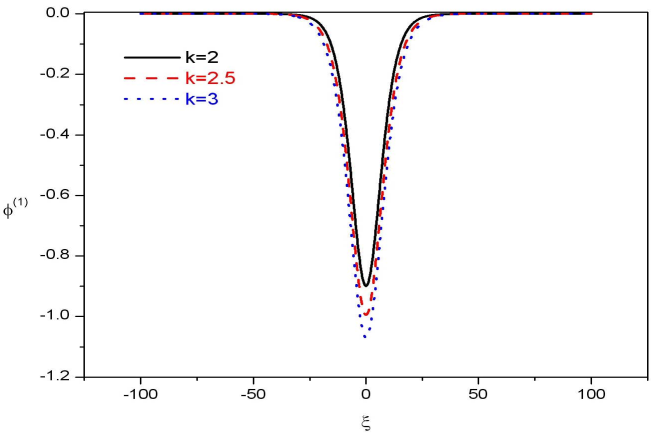

Fig. 4. Cylindrical SWs: $\varphi^{(1)}$ versus ξ at $\tau = -1.6$ for different values of k, with $\sigma = 0.5$ and $\mu = 0.05$.

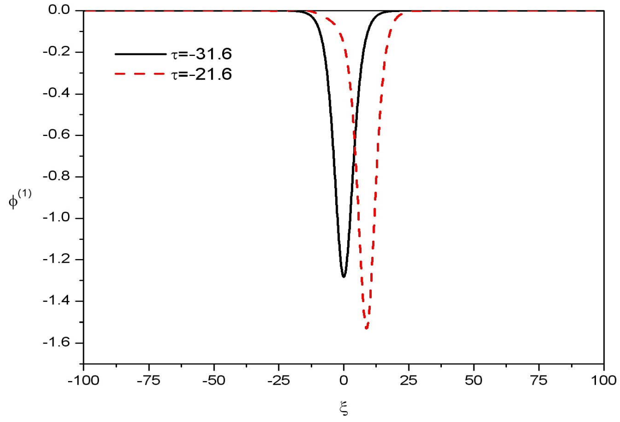

Fig. 5. Time evolution of cylindrical SWs: $\varphi^{(1)}$versus ξ at $\tau = -1.6, -21.6$ with $\sigma = 0.2$, $\mu = 0.1$ and k = 1.6.

compression and rarefaction revealing therefore that the fully nonlinear behavior may be preserved to a large extent in the weak nonlinear regime. It may be noted that in Fig. 3 coefficient of A is plotted against σ for different values of k with $\mu = 0.3$ and $\nu = 1$. Similar behavior is observed for the spherical geometry (figure not shown). Bacha *et al.* [23] showed that DIA appears as rarefactive and compressive SWs in the present of nonextensive electrons. They showed that the variation of DIA soliton amplitude is different for small and/or large values of nonextensive parameter [23]. Fig. 4 shows cylindrical rarefactive DIASWs for different values of k with $\mu = 0.05$, $\sigma = 0.5$ at $\tau = -31.6$. The temporal evolution of the rarefactive DIA solitons in a dusty plasma for cylindrical geometry is also shown in Fig. 5 for $\mu = 0.1$, $\sigma = 0.2$, and $k = 1.6$. It is obvious that the amplitude of cylindrical and spherical solitons increase rarefactively with increasing superthermality in such plasma. These results are also agreed with [19] for cylindrical and spherical DIASWs in an unmagnetized dusty plasma, whose constituents are inertial ions, Boltzmann electrons, and stationary dust particles. To see the effect of ion-to-electron temperature ratio (σ) on the characteristics of DIASWs, the time evolution of cylindrical DIAWs excitation is plotted against ξ for different values of

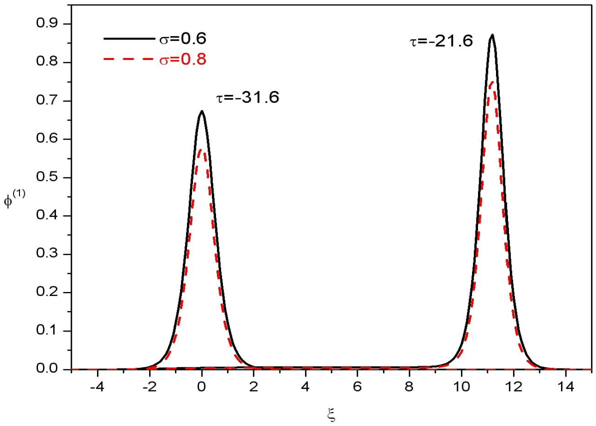

Fig. 6. Time evolution of cylindrical SWs: $\varphi^{(1)}$ versus ξ at $\tau = -1.6, -21.6$ for different values of σ, with $\mu = 0.9$ and k = 1.6.

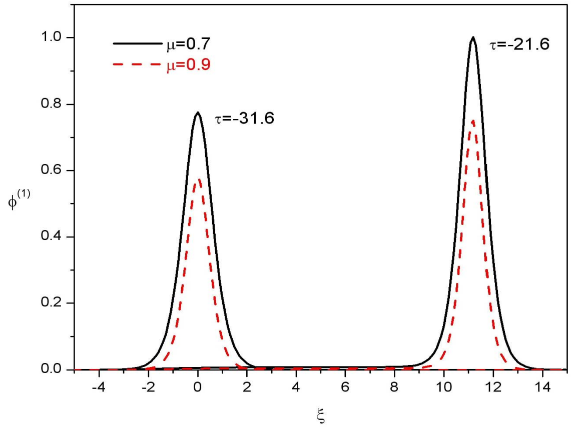

Fig. 7. Time evolution of cylindrical SWs: $\varphi^{(1)}$versus ξ at $\tau = -1.6, -21.6$ for different values of μ, with $\sigma = 0.8$ and k = 1.6.

σ, viz., $\sigma = 0.6$, and $\sigma = 0.8$, as shown in Fig. 6. Other parameters are $k = 1.6$ and $\mu = 0.9$. From this figure, it is shown that increasing of σ leads to the decrease in the soliton amplitude. Thus increase in the ion temperature (relative to electron) decreases the soliton amplitude. It is also found that the cylindrical solitons travel slower than the spherical solitons (figure not shown). Fig. 7 shows the effect of increasing of the value of μ on the amplitude of DIASWs. It is clear that increasing the amount of dust in this system leads to increasing amplitudes of the DIASWs. The other parameters are as follows: $\sigma = 0.8$ and $k = 1.6$. It is worth mentioning here that the dust density can be expressed by the variation of μ because of $n_{d0}/n_{e0} = (1 - \mu)/\mu$. The above results can be compared with other investigations. Mamun *et al.* [48] showed that the amplitude of DIASWs decreases with the increase of the trapping parameter of vortexlike electron distribution. Alinejad [49] showed that an increase of the nonthermal electron concentration can be leads to a decrease of the soliton amplitude. Tribeche *et al.* [50] investigated the effect of electron nonthermality on the large amplitude electrostatic SWs in a charge varying dusty plasma. They found that the nonlinear localized structure with positive potential shrinks when the electron deviates from isothermality.

V. CONCLUSION

In conclusion, we have investigated the nonplanar cylindrical and spherical DIASW that is governed by the modified KdV equation in an unmagnetized dusty plasma, whose constituents are adiabatic ion fluid, superthermal electrons, and negatively charged static dust particles. The ranges of different plasma parameters used in this investigations are very wide ($0.05 < \mu < 0.9$ and $0 < \sigma < 1$), and are relevant to [22], [52], [53]. To have some numerical appreciations of our results, values of sigma parameter corresponding to the Saturn rings (E ring and F ring) [53] and [54]. Thus, the results of the present investigation may help us to explain the basic features of DIASWs propagating in space [5], [6] and laboratory [55] dusty plasmas. The nonplanar geometry effect for DIASW is very strong for a small value of $|\tau|$ and there are obvious differences between the cylindrical and spherical DIASWs. It is seen that amplitude increases with increase in τ as well as the value of superthermal parameter k. Furthermore, we see that a small value of k and thus an increase in superthermality increases the value of speed of DASWs. It is also found that the amplitude of cylindrical SWs is smaller than that of the spherical ones. It may be noted that because of electron superthermality and also other plasma parameters the DIASW may exhibit either a compression or a rarefaction. The amplitude of DIASW decreases with increasing of μ (decreasing of dust density) and ion temperature. The purpose of studying the nonplanar bounded plasma is to gain understanding on the propagation characteristics of the DIAWs that are of vital importance in laboratory plasmas as well as in plasma application. We also stress that the present results may help to understand the salient features of the cylindrical/spherical DIASWs when data for laboratory observations become available. It is also important to mention that the DIASWs are more suitable than the DAWs to observe in laboratory dusty plasma conditions.

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Authors' photographs and biographies not available at the time of publication.